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(54) Title: SELF-VALIDATING SENSORS
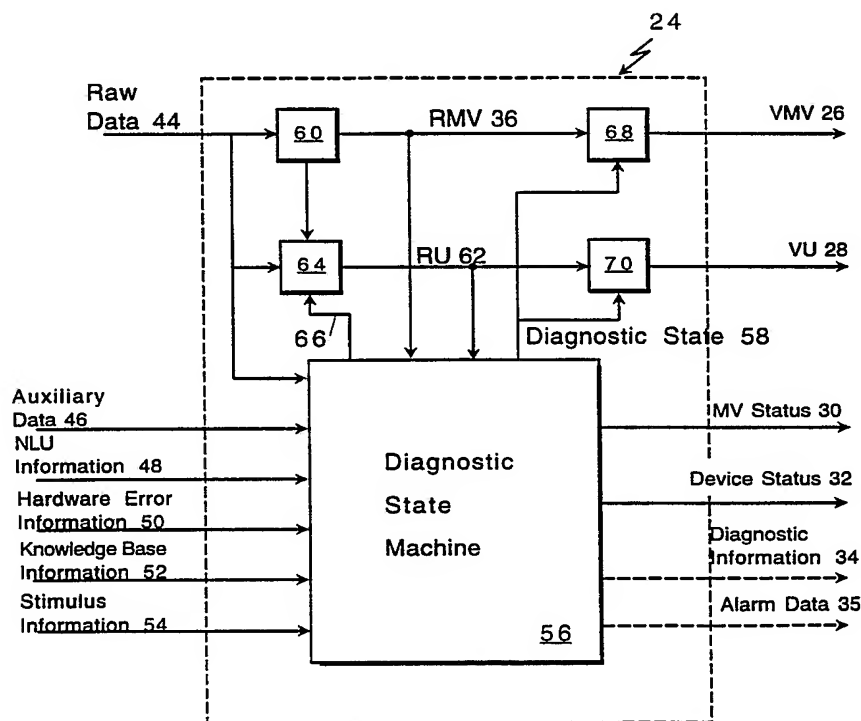
(57) Abstract

A sensor provides a measurement and information about the validity of the measurement. The sensor includes a transducer for generating a data signal related to the value of a variable and a transmitter for receiving the data signal and generating output signals. The transmitter generates a first output signal related to the value of the variable. The transmitter also generates a second output signal based on a dynamic uncertainty analysis of the first output signal.

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<u>SELF-VALIDATING SENSORS</u>
<u>Background of the Invention</u>

This invention relates to sensors and to control
5   systems incorporating sensors.

A sensor generates measurement data. Typically,
the measurement data is a signal that estimates the value
of a process variable. In practice, the signal does not
perfectly represent the value of the process variable.
10 Instead, the signal also includes effects resulting from
the sensor (such as sensor faults or distortion) and
other process influences (including those attributable to
"faulty" process behavior).

Sensor and control system designers employ
15 numerous techniques to increase the reliability of
measurement data. For example, sensor designers try to
develop improved sensor designs that minimize both the
occurrence of sensor faults and the distortions occurring
during normal operation. In another approach, control
20 system designers implement rigorous programs of sensor
checking, maintenance, and calibration to reduce both the
frequency at which sensor faults occur and the distortion
caused by poorly maintained sensors.

In conjunction with increasing the reliability of
25 measurement data, designers employ fault detection
techniques to increase a control system's ability to
recognize that measurement data is unreliable. For
example, control system designers often rely on sensor
redundancy to reduce the effect of any sensor fault that
30 may occur. If measurement data from a sensor in a group
of redundant sensors is inconsistent with measurement
data from other sensors in the group, a control system
can designate the inconsistent data as unreliable and
ignore that data.

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In another approach to fault detection, control
systems monitor information about the process and the
sensor for signs of sensor faults. Until recently,
sensors have been limited to a single analog
5   communication channel, normally based on the 4-20mA
convention, and, therefore, have been unable to transmit
signals other than a measurement data signal. Faced with
this limitation, users of process fault detection
techniques have tried to extract sensor and process fault
10   information from measurement data. However, in
attempting to minimize distortion of the measurement
data, sensor designers have tried to eliminate, by
sophisticated filtering and other means, every component
of the measurement data signal that does not actually
15   relate to the variable being measured. Thus, improved
sensor designs have limited the information available for
extraction from the measurement signal for fault
detection purposes.

Recent use of digital communications technology by
20   control system designers has enabled sensors to transmit
multiple signals. This, in combination with internal
diagnostics generated by microprocessors, which are now
commonly embedded within sensors, has resulted in sensors
that are able to perform fault detection analyses
25   internally and transmit the results of these analyses as
a fault information signal. Typically, the fault
information signal is either a device specific error code
or a single bit which indicates that the sensor is either
functional or nonfunctional.

30   Summary of the Invention

The invention provides a self-validating sensor
for use in process control systems. A self-validating
sensor provides, based on all information available to
the sensor, a best estimate of the value of a parameter
35   being monitored. Because the best estimate is based, in

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part, on nonmeasurement data, the best estimate does not always conform to the value indicated by the current, possibly faulty, measurement data. A self-validating sensor also provides information about the uncertainty
5 and reliability of the best estimate, as well as information about the operational status of the sensor. Uncertainty information is derived from known uncertainty analyses and is provided even in the absence of faults.

In one aspect, generally, the invention features a
10 sensor that includes a transducer that generates a data signal related to the value of a variable and a transmitter that receives the data signal and generates output signals in response. The transmitter generates a first output signal related to the value of the variable
15 and a second output signal based on a dynamic uncertainty analysis of the first output signal. When the sensor experiences a fault, the transmitter modifies the first and second output signals to account for the impact of the fault. In some embodiments, the transmitter
20 generates a third output signal that indicates a state of reliability of the first output signal.

The second output signal, which provides on line uncertainty, can be used for data quality management. A specified maximum permitted uncertainty can be used, for
25 example, in specifying plant instrumentation, supervising feedback control, scheduling maintenance, and demonstrating adequate data quality for environmental compliance or custody transfer applications.

Generally, the invention provides a standard,
30 device-independent method of communicating sensor faults and measurement quality, which eases integration into control schemes. In some cases, this avoids the cost of sensor redundancy and constant calibration programs, which, in any large or complicated process plant, are
35 quite costly and of dubious value.

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The invention also eases implementation of fault
detection schemes by supplying a common set of variables
in a generic form for use by control systems and
requiring sensor designers, who are in the best position
5 to recognize and define faulty behavior, to implement the
actual fault detection in the sensors themselves.

<u>Brief Description of the Drawing</u>

Fig. 1 is a block diagram of a process control
system with multiple sensors and actuators.

10   Fig. 2 is a block diagram of a sensor according to
the invention.

Fig. 3 is a block diagram showing the flow of
information in the sensor of Fig. 2.

Fig. 4 is a composite graph showing three methods
15 of responding to a fault in the sensor of Fig. 2.

Fig. 5 is a composite graph of various signals
produced by the sensor of Fig. 2 versus time.

Fig. 6 is a block diagram showing the timing of
information flow in the sensor of Fig. 2.

20   Fig. 7 is a block and schematic diagram of a
temperature sensor according to the invention.

Fig. 8 is a set of composite graphs of an
auxiliary signal (upper graph), raw temperature (middle
graph), and validated temperature and uncertainty (lower
25 graph) versus time for the instrument of Fig. 7.

Fig. 9 is a set of composite graphs of raw data
(upper graph), raw temperature (middle graph) and
validated temperature and uncertainty (lower graph)
versus time for the instrument of Fig. 7.

30   Fig. 10 is a paired composite graph of auxiliary
data (upper graph) and validated temperature and
uncertainty (lower graph) for the instrument of Fig. 7.

Fig. 11 is a schematic and block diagram of a
Coriolis flow meter.

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Fig. 12 is pseudocode showing steps performed by the meter of Fig. 11 during each sampling period.

Fig. 13 is pseudocode showing steps performed by the meter of Fig. 11 in determining temperature and 5 associated uncertainty.

Fig. 14 is pseudocode showing steps performed by the meter of Fig. 11 in diagnosing a fault.

Fig. 15 is a set of composite graphs showing the effect of a loss of temperature on temperature (upper 10 graphs), density (middle graphs) and mass flow rate (lower graphs) versus time for the meter of Fig. 11.

<u>Description of the Preferred Embodiments</u>

Referring to Fig. 1, in a process control system 10, a plurality of sensors 12 monitor parameters of a 15 process 14 and provide signals about the monitored parameters to a data control and management system 16 on a digital communications link 18. Digital communications link 18 allows bidirectional communication between multiple central processing units 16, sensors 12, and 20 process actuators 20. In response to signals from sensors 12, data control and management system 16 sends process control signals to process actuators 20 on digital communications link 18. Thereafter, process actuators 20 respond to process control signals from data 25 control and management system 16 by modifying parameters of process 14.

Because data control and management system 16 relies on measurement signals from sensors 12 in controlling process 14, measurement signals from sensors 30 12 need to be accurate and reliable. A given sensor 12 typically cannot guarantee complete accuracy and reliability; instead, sensor 12 provides data control and management system 16 with indications of the uncertainty (which, in turn, indicates the accuracy) and the 35 reliability of the measurement signals.

Referring also to Fig. 2, sensor 12 includes one
or more transducers 22 that monitor the values of
parameters of process 14 and provide signals to a
transmitter 24. Transmitter 24 samples the signals from
5   transducers 22 and produces measurement values for the
parameters being monitored by transducers 22.
Transmitter 24 validates the measurement values and
provides the validated measurement values, along with an
indication of the uncertainty of the validated
10 measurement values, to data control and management system
16 via digital communications link 18. In addition,
transmitter 24 generates signals indicating the
reliability of the validated measurement values provided
by sensor 12 and the operational status of sensor 12, and
15 provides these signals to data control and management
system 16 via digital communications link 18.

Transmitter 24 generates the signals provided to
data control and management system 16 during a sample
period and transmits the signals at the end of the sample
20 period. Typically, the duration of a sample period is
less than one second, but this duration can be adjusted
as required by a particular application.

As shown in Fig. 3, transmitter 24 typically
provides four signals to data control and management
25 system 16:

> (1)   VMV 26 - a validated measurement value of a
>   process parameter (transmitter 24's best
>   estimate of the value of the measured
>   parameter),
>
30 > (2)   VU 28 - a validated uncertainty associated
>   with VMV 26,
>
> (3)   MV status 30 - the status of VMV 26 (the
>   manner in which VMV 26 was calculated), and
>
> (4)   device status 32 - the operational status of
35 >   the sensor.

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If sensor 12 measures multiple process parameters, transmitter 24 produces a version of VMV 26, VU 28, and MV status 30 for each process parameter.

In some circumstances, transmitter 24 can provide
5   additional information. For example, upon a request by data control and management system 16, transmitter 24 provides detailed diagnostic information 34 about the status of sensor 12. Also, when a measurement has exceeded, or is about to exceed, a predetermined limit,
10 transmitter 24 can send alarm data 35. Typically, different alarm levels can be used to indicate the severity with which the measurement has deviated from the predetermined value.

VMV 26 and VU 28 are numeric values. For example,
15 VMV 26 could be a temperature measurement valued at 200 degrees and VU 28, the uncertainty of VMV 26, could be 9 degrees. In this case, there is a high probability (typically 95%) that the actual temperature being measured falls within an envelope around VMV 26 and
20 designated by VU 28 (191 degrees to 209 degrees).

Transmitter 24 generates VMV 26 based on a signal produced by transducer 22. First, transmitter 24 derives RMV 36, an unvalidated image of the measured process parameter that is based on the signal generated by
25 transducer 22. Typically, when transmitter 24 detects no abnormalities in sensor 12, transmitter 24 has nominal confidence in RMV 36 and sets VMV 26 equal to RMV 36.

As discussed in more detail below, when transmitter 24 detects an abnormality in sensor 12,
30 transmitter 24 does not set VMV 26 equal to RMV 36. Instead, transmitter 24 sets VMV 26 to a value that transmitter 24 considers to be a better estimate of the actual parameter than RMV 36. If transmitter 24 detects a fault in sensor 12 that only partially affects the
35 reliability of RMV 36 such that transmitter 24 has

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reduced confidence in RMV 36, transmitter 24 typically
rederives RMV 36 by modifying the parameters used in
deriving RMV 36 to account for the fault, and sets VMV 26
equal to the new value of RMV 36. Alternatively, if
5 transmitter 24 detects a fault in sensor 12 which
indicates that RMV 36 bears no relation to the actual
measured value such that transmitter 24 has zero
confidence in RMV 36, transmitter 24 sets VMV 26 to a
value based on past performance.

10   Referring also to Fig. 4, three examples of past
performance values include short term past values, long
term past values, and a combination of long and short
term past values. As shown in (a), when short term past
values are used, VMV 26 can equal the value of VMV 26 had
15 immediately prior to the fault that occurs at time 5. As
shown in (b), when long term past value are used, VMV 26
can equal the average value of VMV 26. As shown in (c),
when a combination of long and short term past values is
used, the long and short term past values can be combined
20 using the following equation, which weighs each value
according to its uncertainty:

$$VMV_{L\&S} = \frac{VU_L^2}{VU_L^2 + VU_S^2} * VMV_S + \frac{VU_S^2}{VU_L^2 + VU_S^2} * VMV_L$$

25 where VU_L and VU_S are the long and short term past values
for VU 28 and VMV_L and VMV_S are the long and short term
past values for VMV 26.

        Transmitter 24 generates VU 28 based on a raw
uncertainty signal, RU 62, that is the result of a
30 dynamic uncertainty analysis of RMV 36. Transmitter 24
performs this uncertainty analysis during each sampling
period.   Uncertainty analysis, originally described in
"Describing Uncertainties in Single Sample Experiments,"
S.J. Kline & F.A. McClintock, Mech. Eng., 75, 3-8 (1953),
35 has been widely applied and has achieved the status of an
international standard for calibration. Essentially, an

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uncertainty analysis provides an indication of the
"quality" of a measurement. Every measurement has an
associated error, which, of course, is unknown. However,
a reasonable limit on that error can often be expressed
5 by a single uncertainty number (ANSI/ASME PTC 19.1-1985
Part 1, Measurement Uncertainty: Instruments and
Apparatus).

As described by Kline & McClintock, for any
observed measurement M, the uncertainty in M, w_M, can be
10 defined as follows:

$$M_{true} \in [M - w_M, \ M + w_M]$$

where M is true (M_{true}) with a certain level of confidence
(typically 95%). This uncertainty is readily expressed
in a relative form as a proportion of the measurement
15 (i.e. w_M/M).

A propagation rule exists for obtaining the
uncertainties of arbitrary functions of primary
measurements. For example, for an arbitrary function R
of variables X, Y, and Z,

20                         $$R = R(X,Y,Z)$$

the uncertainty of R is given by

$$[w_R/R]^2 = [\partial R/\partial X]^2 \ [w_X/R]^2 + [\partial R/\partial Y]^2 \ [w_Y/R]^2$$
$$+ [\partial R/\partial Z]^2 \ [w_Z/R]^2$$

This sum of squares form is derived from the Taylor
25 series, and assumes the independence of X, Y, and Z, that
their relative uncertainties are "small", and that all
uncertainties are expressed at the same probability
level. For purposes of this application, all
uncertainties are assumed to be at 95% probability.

30   One of the uses of the uncertainty propagation
formula is to reveal particular circumstances that can
result in a higher or lower than expected level of
uncertainty. For example, as discussed in S.J. Kline,
"The Purposes of Uncertainty Analysis", ASME Journal of

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Fluids Engineering, Vol. 107, No. 2, pp. 153-160, 1985,
if R is calculated from x and y using the equation

$$R = x - y,$$

the uncertainty in R, w_R, is given by

5      $$w_R/R = [(x/(x-y) * w_x/x)^2 + (y/(x-y) * w_y/y)^2]^{1/2}.$$

If $x = 1.0$, $y = 0.98$, and the uncertainty in both x and y
is 1%, then the uncertainty in R is:

$$w_R/R = [(1/0.02 * 0.01)^2 + (0.98/0.02 * 0.01)^2]^{1/2}$$
$$= 0.700 = 70\%.$$

10 By comparison, if R is calculated from a variable z using
the equation

$$R = (1/(1 + z))^{1/2},$$

the uncertainty in R is given by

$$w_R/R = w_z/2(1 + z).$$

15 If $z = 0.1$ and the uncertainty is z is 20%, then the
uncertainty in R is only 0.91%.

On reflection these results should not be
surprising. In the first example, two quantities of
similar magnitude are being subtracted, which will

20 increase the relative error in the result. In the
second, although z has a large uncertainty, its influence
on R is relatively small. Of course, for different
values of x, y, and z, the impact of their uncertainties
will vary. Uncertainty analysis is useful in that it can

25 quantify these effects.

Returning to Fig. 3, VU 28 has a non-zero value
even under ideal conditions (i.e., a faultless sensor
operating in a controlled, laboratory environment). This
is because the measurement produced by a sensor is never

30 completely certain and there is always some potential for
error.

As with VMV 26, when transmitter 24 detects no
abnormalities in sensor 12, transmitter 24 sets VU 28
equal to RU 62. When transmitter 24 detects a fault in

35 sensor 12 that only partially affects the reliability of

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RMV 36, transmitter 24 typically performs a new
uncertainty analysis that accounts for effects of the
fault and sets VU 28 equal to the results of this
analysis. As with VMV 26, transmitter 24 sets VU 28 to a
5   value based on past performance when transmitter 24
determines that RMV 36 bears no relation to the actual
measured value.

        Fig. 4 illustrates three exemplary techniques for
adjusting VU 28 based on past performance values. First,
10 as shown in (a), VU 28 can be increased during each
sampling period by the maximum observed rate of change of
VMV 26. This technique, which tends to give good short
term results, eventually produces unrealistic values for
VU 28. Next, as shown in (b), when VMV 26 is set equal
15 to the long term average of VMV 26, VU 28 can indicate
that VMV 26 can take any previous value of VMV 26. Thus,
if VMV 26 always falls between 0 and 100 and VMV 26 is
set to 50, VU 28 is set to 50. This technique tends to
give unduly pessimistic short term results, but avoids
20 the long term problems of method (a). Finally, as shown
in (c), when VMV 26 is based on a combination of the long
and short term past values for VMV 26, VU 28 can be
calculated as follows:

$$25 \qquad VU_{L\&S} = \frac{VU_L * VU_S}{(VU_L{}^2 + VU_S{}^2)^{1/2}}$$

where VU_L and VU_S are the long and short term past values
for VU 28.

        To ensure that data control and management system
30 16 uses VMV 26 and VU 28 properly, MV status 30 provides
information about how VMV 26 and VU 28 were calculated.
Transmitter 24 produces VMV 26 and VU 28 under all
conditions--even when transducers 22 are inoperative.
Often, data control and management system 16 needs to
35 know whether VMV 26 and VU 28 are based on "live" or
historical data. For example, if data control and

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management system 16 were using VMV 26 and VU 28 in
feedback control and transducers 22 were inoperative,
data control and management system 16 would need to know
that VMV 26 and VU 28 were based on past performance.

5   MV status 30 is based on the expected persistence
of any abnormal condition and on the confidence of
transmitter 24 in RMV 36. The four primary states for MV
status are generated according to Table 1.

Table 1

Expected Persistence	Confidence in RMV	MV Status
not applicable	nominal	CLEAR
not applicable	reduced	BLURRED
short	zero	DAZZLED
long	zero	BLIND

          A CLEAR MV status 30 occurs when RMV 36 is within
a normal range for given process conditions. A DAZZLED
MV status 30 indicates that RMV 36 is quite abnormal, but
the abnormality is expected to be of short duration.
20 Typically, transmitter 24 sets MV status 30 to DAZZLED
when there is a sudden change in the signal from
transducer 22 and transmitter 24 is unable to clearly
establish whether this change is due to an as yet
undiagnosed sensor fault or to an abrupt change in the
25 variable being measured. A BLURRED MV status 30
indicates that RMV 36 is abnormal but reasonably related
to the parameter being measured. For example,
transmitter 24 may set MV status 30 to BLURRED when RMV
36 is a noisy signal. A BLIND MV status 30 indicates
30 that RMV 36 is completely unreliable and the fault is
expected to persist.
          Two additional states for MV status 30 are
UNVALIDATED and SECURE. MV status 30 is UNVALIDATED when

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transmitter 24 is not performing validation of VMV 26.
MV status 30 is SECURE when VMV 26 is generated from
redundant measurements in which transmitter 24 has
nominal confidence.

5   Device status 32 is a generic, discrete value
summarizing the health of sensor 12 that is used
primarily by fault detection and maintenance systems.
Typically, device status 32 is in one of six states, each
of which indicates a different operational status for

10 sensor 12. These states are: GOOD, TESTING, SUSPECT,
IMPAIRED, BAD, or CRITICAL. A GOOD device status 32
means that sensor 12 is in nominal condition. A TESTING
device status 32 means that sensor 12 is performing a
self check, and that this self check

15   may be responsible for any temporary reduction in
measurement quality. A SUSPECT device status 32 means
that sensor 12 has produced an abnormal response, but
transmitter 24 has no detailed fault diagnosis. An
IMPAIRED device status 32 means that sensor 12 is

20 suffering from a diagnosed fault that has a minor impact
on performance. A BAD device status 32 means that sensor
12 has seriously malfunctioned and maintenance is
required. Finally, a CRITICAL device status 32 means
that sensor 12 has malfunctioned to the extent that

25 sensor 12 may cause (or have caused) a hazard such as a
leak, fire, or explosion.

          Fig. 5 illustrates an example of the relationship
between VMV 26, VU 28, MV status 30, and RMV 36. In
another aspect, Fig. 5 illustrates a preferred method of

30 displaying the relationship between VMV 26 and VU 28 both
during normal operation and when a fault has occurred:
VU 28 is shown both as a separate signal and as an
envelope surrounding VMV 26 (line 38 indicates the sum of
VMV 26 and VU 28 and line 40 indicates the difference

35 between VMV 26 and VU 28). When VU 28 is expressed as an

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envelope surrounding VMV 26, a user can, by examining the
envelope, visually determine the range of probable values
of the parameter represented by VMV 26 for any displayed
time.

5   In the region between time T1 and time T2, RMV 36
is a periodic signal whose amplitude falls within an
expected range. In this region, VMV 26 equals RMV 36, MV
status 30 is CLEAR, and VU 28 remains at a constant
"normal" level that corresponds to RU 62, the uncertainty
10 under normal operating conditions (with line 42
representing a zero value for VU 28). For purposes of
this example, RU 62 is assumed to have a constant value.
          At time T2, RMV 36 begins to increase at a rate
that substantially exceeds an expected rate of change for
15 RMV 36. Transmitter 24 takes a number of actions in
response to this unexplained phenomenon. First,
transmitter 24 changes MV status 30 to DAZZLED. Next,
transmitter 24, which is basing VMV 26 and VU 28 on short
term past performance values in this example, maintains
20 VMV 26 at the value that VMV 26 had just before the
sudden increase in RMV 36 at time T2. Finally,
transmitter 24 begins to increase VU 28 at a constant
rate that equals the maximum rate of increase of VMV 26
during normal operation. The progressive increase in the
25 value of VU 28 over time reflects increasing uncertainty
of the value of the measurement in the absence of up to
date valid transducer data caused by sensor 12 being
DAZZLED.
          RMV 36 continues to increase until time T3. At
30 time T3, RMV 36 stops increasing and remains at a
constant level. Because the value of RMV 36 now exceeds
expected values, transmitter 24 does not change VMV 26 or
MV status 30, and continues to increase VU 28 at a
constant rate. At time T4, RMV 36 begins to decrease.
35 Because the value of RMV 36 still exceeds expected

values, transmitter 24 makes no changes to VMV 26 or MV
status 30, and continues to increase VU 28 at a constant
rate.

5   At time T5, RMV 36 begins to operate as expected.
In response, transmitter 24 changes MV status 30 to
BLURRED and begins to merge VMV 26 with RMV 36 using, for
example, the following equation:

$$VMV_{n+1} = 0.95 * VMV_n + 0.05 * RMV_{n+1}$$

where VMV_{n+1} is the value of VMV 26 for the current
10   sample, VMV_n is the value of VMV 26 generated in the
previous sample, and RMV_{n+1} is the value of RMV 36 for the
current sample. Next, transmitter 24 initializes a
recovery timeout period. Finally, transmitter 24 begins
to decrease VU 28 by merging VU 28 with RU 62 using, for
15   example, the following equation:

$$VU_{n+1}{}^2 = 0.95^2 * VU_n{}^2 + 0.05^2 * RU_{n+1}{}^2$$

where VU_{n+1} is the value of VU 28 for the current sample,
VU_n is the value of VU 28 generated in the previous
sample, and RU_{n+1} is the value of RU 62 for the current
20   sample.

At time T6, transmitter 24 determines that the
recovery timeout period has expired and changes MV status
30 to CLEAR. Because transmitter 24 now has nominal
confidence in RMV 36, transmitter 24 sets VU 28 equal to
25   RU 62.

If, at time T5, RMV 36 had not returned to
expected levels, sensor 12 would have either maintained
MV status 30 as DAZZLED or diagnosed a sensor fault and
changed MV status 30 to BLIND. MV status 30 can only be
30   DAZZLED for a limited "timeout" period. Thus, if RMV 36
remained at unexpected levels, the timeout period would
eventually expire, and transmitter 24 would change MV
status 30 to BLIND.

As shown in Fig. 3, transmitter 24 uses several
35   sources of information, each of which is discussed below,

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in generating VMV 26, VU 28, MV status 30, device status
32, diagnostic information 34, and alarm data 35. Raw
data 44, the basic measurement information available to
transmitter 24, is typically an electrical image of the
5   output of one or more transducers 22 (e.g., the frequency
of oscillation or the resistance of a transducer 22).
Raw data 44 contains the maximum information available
about the response of transducer 22 and is therefore a
rich source of information for statistical tests to
10 detect sensor faults. However, knowledge of expected
process behavior cannot be applied readily to raw data 44
and is more appropriately applied to statistics based on
RMV 36.

Because RMV 36 directly relates to a process
15 parameter (e.g., temperature or mass flow rate),
transmitter 24 can link the expected (no-fault) behavior
of RMV 36 to the expected behavior of the process
parameter associated with RMV 36. Transmitter 24 derives
RMV 36 from raw data 44 by conventional processing. For
20 example, if raw data 44 corresponds to the resistance of
a transducer 22 and RMV 36 corresponds to temperature,
transmitter 24 derives RMV 36 based on raw data 44 in
light of known effects of temperature on the resistance
of transducer 22. Often, transmitter 24 filters RMV 36
25 to reduce the effect of sensor noise and high frequency
process disturbances. When filtering occurs, RMV 36
contains less information than raw data 44.

To a certain extent, raw data 44 and RMV 36 are
complementary sources of information. While raw data 44
30 has more information content than RMV 36, RMV 36 is more
easily compared with expected process behavior. Thus,
raw data 44 and RMV 36 each offer useful information to
transmitter 24.

Auxiliary data 46 is provided by auxiliary signals
35 within sensor 12. Auxiliary signals, though not directly

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related to raw data 44 or RMV 36, give useful information
about the health or performance of sensor 12. For
example, statistical tests to identify characteristic
sensor or process behavior may be associated with
5 particular auxiliary signals. Examples of auxiliary
signals include the electrical properties of components
within sensor 12 (e.g., signal levels at the input or
output stages of power amplifiers) and hardware error
information 50. Hardware error information 50 is a
10 special, preprocessed form of auxiliary information
generated by digital components within sensor 12,
requiring little or no processing or interpretation. For
example, a memory checksum error in a memory component of
transmitter 24 would constitute hardware error
15 information 50.

     In addition to information from within sensor 12
or from process 14, transmitter 24 uses information from
data control and management system 16 in generating
output signals. Data control and management system 16 is
20 known as the "Next Level Up" ("NLU"), and information
from data control and management system 16 is known as
NLU information 48. A difficulty associated with having
transmitter 24 validate the output of sensor 12 is that
transmitter 24 may have insufficient information to reach
25 a valid conclusion. For example, transmitter 24 may be
unable to distinguish between certain types of sensor
faults (e.g., drift errors that cause the output of the
sensor to change over time for a given input) and
legitimate process changes. In these situations,
30 transmitter 24 may refer to NLU information 48 for
clarification. Data control and management system 16,
which has access to additional information, including
data from other sensors 12, provides transmitter 24 with
the information needed to distinguish between process
35 changes and sensor drift.

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Transmitter 24 may request NLU information 48 such
as anticipated process limits through standard requests
to data control and management system 16. Alternatively,
data control and management system 16 can provide
5 unsolicited information, such as indications of changes
in process behavior that will change the process
parameters being measured by transducers 22, to
transmitter 24. For example, if process 14 operates in a
number of phases that each have distinct characteristics,
10 data control and management system 16 can notify
transmitter 24 when the phase of process 14 changes.

Application knowledge base information 52 allows
transmitter 24 to estimate a "wear and tear" effect on
sensor performance. Application knowledge base
15 information 52 describes the relationship between signals
and sensor characteristics over time. In some
applications, sensors are known to degrade much more
rapidly under certain conditions (e.g., at extremes of
their operating range). For example, if a normal range
20 pH probe is exposed to more than about 12pH for as little
as an hour, the probe may become alkali-conditioned and
fail to respond when the solution becomes more acidic.
Application knowledge base information 52 also includes
factors such as the time elapsed since the last
25 calibration or last maintenance of sensor 12.

Sensor/process stimulus information 54 provides
information about a known stimulus applied to the process
or part of a sensor. Sensor/process stimulus information
54 is used in implementing procedures for testing sensor
30 12. A known stimulus is applied to process 14 or sensor
12 and the response generated by sensor 12 is compared
with an expected response. For example, sensor/process
stimulus information 54 could describe a known force that
has been introduced to a pressure transducer.
35 Sensor/process stimulus information 54 is generated by

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transmitter 24 (i.e., as part of a self-test initiated by
transmitter 24) or sent by data control and management
system 16 as NLU information 48. When testing disables
the measuring capability of sensor 12, transmitter 24
5   sets the MV status 30 of each disabled measurement to
DAZZLED, bases VMV 26 and VU 28 on past performance, and
sets device status 32 to TESTING.

   Fig. 3 also shows the functional units of
transmitter 24. A diagnostic state machine 56 processes
10 all of the information available to transmitter 24 and
determines the diagnostic state 58 of sensor 12.
Diagnostic state 58 is the central piece of information
used by diagnostic state machine 56 in deriving VMV 26,
VU 28, MV status 30, and device status 32. Because
15 diagnostic state 58 may itself be helpful to users
performing maintenance on sensor 12, it is the basis of
diagnostic information 34, which is output upon a request
by data control and management system 16.

   Referring also to Fig. 6, transmitter 24 performs
20 the following operations during each sampling period.
After getting raw data 44 from transducer 22 (step 72),
diagnostic state machine 56 propagates raw data 44
through a set of device equations 60 to generate RMV 36
(step 74). At the same time, transmitter 24 dynamically
25 calculates RU 62 using an uncertainty analysis 64 based
on device equations 60 and calibration data 66 in
accordance with the established standards discussed above
(step 74). In calculating RU 62, transmitter 24 assumes
that no fault has occurred. RU 62 has a non-zero value
30 under all operating conditions. Generally, RU 62
increases under other than ideal conditions.

   Next, diagnostic state machine 56 obtains other
information (step 76) and, based on the other
information, raw data 44, RMV 36, and RU 62, calculates
35 statistics or performs pattern matching to determine if

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sensor 12 is operating correctly (step 78). Based on the results of step 78, diagnostic state machine 56 updates diagnostic state 58 (step 80).

Next, diagnostic state machine 56 modifies (68)
5   RMV 36 based on diagnostic state 58 to produce VMV 26.
Essentially, diagnostic state machine 56 recalculates RMV 36 after modifying the parameters used in the calculation to account for diagnostic state 58 and sets VMV 26 equal to the new RMV 36 (step 82). Thus, under normal
10 operating conditions (when diagnostic state 58 does not require modification of any parameters), VMV 26 typically equals RMV 36.

At the same time, diagnostic state machine 56 modifies (70) RU 62 based on diagnostic state 58 to
15 produce VU 28. As with VMV 26, diagnostic state machine 56 recalculates RU 62 after modifying the parameters used in the calculation to account for diagnostic state 58 and sets VU 28 equal to the new RU 62 (step 82). Thus, VU 28 typically equals RU 62 under normal operating conditions.
20 Under other conditions, VU 28 typically exceeds RU 62.

Next, diagnostic state machine 56 selects MV status 30 (step 84) and device status 32 (step 86) based on diagnostic state 58 and via either calculations or a lookup table. If necessary, diagnostic state machine 56
25 sends alarm data 35 by updating alarm flags (step 88).
Also, if data control and management system 16 has requested it, diagnostic state machine 56 generates diagnostic information 34 based on diagnostic state 58 (step 90).
30   Referring to Fig. 7, a self-validating temperature sensor 100 includes a thermocouple 102 and a transmitter 104 that includes a processor 106. Typically, thermocouple 102 includes two dissimilar metals in contact and produces a voltage, V_{Diff}, between two
35 terminals 108 and 110. V_{Diff} is proportional to the

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difference between the temperature of a sensing junction
112 and a reference junction 114. The sum of V_{Diff} and
V_{Comp}, a voltage proportional to the difference between
the temperature of reference junction 114 and zero

5   degrees, equals V_{Temp}, a voltage proportional to the
difference between the temperature of sensing junction
112 and zero degrees. To determine V_{temp}, V_{diff} is
amplified by amplifier 116 and V_{comp} is generated by
temperature sensor 118 and amplified by amplifier 120.

10   The output 117 of amplifier 116 and the output 121 of
amplifier 120 are then supplied to an analog-to-digital
convertor ("ADC") 122 in processor 106. Processor 106
uses amplifier outputs 117, 121, and other available
information, to generate diagnostic state 58, RMV 36, and

15   RU 62. Based on these signals, processor 106 generates
VMV 26, VU 28, MV status 30, device status 32, alarm data
35, and, when requested, diagnostic information 34.

        Referring to Fig. 8, self-validating temperature
sensor 100 responds to a loss of power to amplifiers 116,

20   120 as described below. During normal operation (time 0
to 15), VMV 26 equals RMV 36, which processor 106
generates based on the sum of outputs 117, 121.
Similarly, VU 28 equals RU 62, and indicates the
uncertainty of VMV 26. MV status 30 is CLEAR.

25   At time 15, the power supply 132 stops functioning
and V_{Diff} and V_{Comp} (outputs 117, 121) both go to zero
volts, which results in an RMV 36 of about negative 55°C
(for a particular transmitter design). Processor 106
detects the loss of power when power monitor 134, a

30   digital auxiliary signal, switches from one to zero in
response to the loss of power. Processor 106 then sets
diagnostic state 58 to indicate that processor 106 has
zero confidence in RMV 36. As a result, processor 106
sets VMV 26 and VU 28 to a combination of the long and

35   short term past values for VMV 26 and VU 28 respectively

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as described above. Finally, processor 106 signals the
severity and expected long term duration of the sensor
fault by setting MV status 30 to BLIND.

5   When the power supply is restored at time 36,
processor 106 detects the change in power monitor 134
from zero to one and sets MV status 30 to BLURRED. The
"live" data from RMV 36 is merged with the previous value
of VMV 26 as described above to give a new value for VMV
10 26. Similarly, RU 62 is merged with the previous value
of VU 28 to give a decreasing value for VU 28. At this
time, processor 106 also initializes a recovery timer.

        Processor 106 generates VMV 26 and VU 28 by
merging past values of VMV 26 and VU 28 with,
respectively, RMV 36 and RU 62 until the recovery timer
15 expires at time 56. (In this example, the recovery timer
was set for 20 seconds.) At that time, processor 106
sets MV status to CLEAR, sets VMV 26 equal to RMV 36, and
sets VU 28 equal to RU 62.

        Referring now to Fig. 9, an open circuit fault
20 occurs at time 13 when thermocouple 102 is disconnected
from transmitter 104. In the presence of such a fault,
RMV 36 is around 130°C, which corresponds to a normal
value for output 121 but an abnormally high value for
output 117 due to saturation of amplifier 116. (Pull-up
25 resistor 136 causes saturation of amplifier 116 in the
presence of an open circuit fault.) In response to the
abnormally high value of output 117, processor 106 sets
diagnostic state 58 to indicate zero confidence in RMV 36
and sets MV status 30 to DAZZLED. Processor 106 then
30 generates VMV 26 and VU 28 based on a combination of the
long and short term past values as described above.

        Next, referring again to Fig. 7, processor 106
connects thermocouple 102 to voltage source 124 via
switch 126 and monitors the voltage 130 produced across a
35 resistor 128. Because of the open circuit, no current

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flows in resistor 128 and voltage 130 is zero volts.
From this, processor 106 confirms the open circuit fault
and sets MV status 30 to BLIND.

5   At time 27, the open circuit fault is corrected
and output 117 returns to a normal value. Processor 106
responds by setting diagnostic state 58 to indicate
reduced confidence in RMV 36 (rather than no confidence),
sets MV status 30 to BLURRED, and initializes a recovery
timer.

10   Thereafter, processor 106 generates VMV 26 and VU
28 by merging past values of VMV 26 and VU 28 with,
respectively, RMV 36 and RU 62 until the recovery timer
expires at time 47 (where the recovery timer was set for
20 seconds). At that time, processor 106 sets MV status
15 to CLEAR, sets VMV 26 equal to RMV 36, and sets VU 28
equal to RU 62.

Referring to Fig. 7, a loss of contact fault
occurs when sensing junction 112 loses contact with the
process element of which the temperature is being
20 measured. Because a loss of contact fault does not
produce an abnormal change in RMV 36, sensor 100 cannot
readily detect the fault.

As a result, sensor 100 uses current injection
tests to detect loss of contact faults. In a current
25 injection test, sensor 100 connects thermocouple 102 to
voltage source 124 for a predetermined period and
measures the effect on output 117. (The value of output
117 before thermocouple 102 is connected to voltage
source 124 is compared to the value after disconnection.)
30   Referring to Fig. 10, a loss of contact fault
occurs at time 12 and the measured temperature drops by
about seven degrees. Because this is within normal
operating parameters, sensor 100 does not immediately
recognize the fault, and, instead, adjusts VMV 26 and
35 maintains MV status 30 as CLEAR.

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At time 28, processor 106 begins a current
injection test. Because amplifier 116 does not read
"live" data during the test, processor 106 sets MV status
30 to DAZZLED and generates VMV 26 and VU 28 based on
5 past performance as discussed above. At time 33,
processor 106 determines that the fault has occurred and
sets MV status 30 to BLURRED. (Processor 106 assumes
that, though contact has been lost, the temperature
sensed by thermocouple 102 still approximates the actual
10 temperature.)

At time 56, contact is reestablished. However,
processor 106 interprets the sudden change in output 117
as a spike and temporarily sets MV status 30 to DAZZLED.
When output 117 remains at the increased value, processor
15 106 sets MV status 30 back to BLURRED. (Processor 106
does not set MV status 30 to CLEAR because processor 106
has not detected the removal of the fault condition.)

At time 66, processor 106 begins another current
injection test and sets MV status 30 to DAZZLED. At time
20 72, processor 106 determines that contact has been
reestablished and, in response, sets MV status to BLURRED
and initializes a recovery timer. At time 97, the
recovery timer (which was set to 25 seconds) expires and
processor 106 sets MV status to CLEAR.

25   Referring to Fig. 11, another example of a self-
validating sensor according to the invention is a
Coriolis flow meter 150. Flow meter 150 measures three
process parameters: mass flow rate, density, and
temperature. Mass flow is measured directly using the
30 principle of Coriolis acceleration, without needing to
rely on external pressure, temperature, or specific
gravity measurements.

Structurally, flow meter 150 consists of a
flowtube 152 that is connected to a transmitter 154 by
35 cables 156. Flowtube 152 includes a body 158 to which is

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connected an input pipe 160 and an output pipe 162. Two
parallel pipe loops 164, 166 extend from body 158. Body
158 contains passages which lead a process fluid from
input pipe 160 to the beginning of loop 164, from the end
5 of loop 164 to the beginning of loop 166 and from the end
of loop 166 to output pipe 162 (the broken arrows in Fig.
11 show the direction of flow in loops 164, 166).

Transmitter 154 causes loops 164, 166 to pivotally
oscillate about their axes of symmetry Y'-Z' and Y-Z by
10 supplying anti-phase sinusoidal signals to
electromagnetic drivers 168, 170. Transmitter 154 uses
feedback to maintain the signals to drivers 168, 170 at
the resonant frequency of loops 164, 166. Transmitter
154 then detects movement of loops 164, 166 via sensors
15 172, 174, which each produce a voltage that is
proportional to the instantaneous velocity between loops
164, 166. Transmitter 154 adjusts the amplitude of the
signals to drivers 168, 170 to maintain the average
amplitude of the voltages produces by sensors 172, 174 at
20 a constant level.

Transmitter 154 measures mass flow rate, density,
and temperature in the following manner. First,
transmitter 154 measures the mass flow rate of the
process fluid by monitoring the effect of Coriolis forces
25 on loops 164, 166. Coriolis forces acting on sections
G'-H' and G-H of oscillating loops 164, 166 cause
deflections of loops 164, 166. These deflections result
in a phase angle difference between the voltages produced
by sensors 172, 174 that is proportional to the mass flow
30 rate. Next, transmitter 154 determines the density of
the process fluid from the frequency of oscillation of
loops 164, 166 (which equals the frequency of the signals
supplied to drivers 168, 170). The density of the
process fluid is inversely proportional to the square of
35 the drive frequency. Finally, transmitter 154 measures

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the temperature of the process fluid via a temperature
sensor 176 located in body 158. Typically, temperature
sensor 176 is an RTD device with a resistance that is
temperature dependent.

5   In the context of flow meter 150, the raw data
available are the frequency 44c of a signal coming out of
temperature sensor 176 (the frequency is proportional to
the resistance of temperature sensor 176), frequency 44b
of the drive signals applied to drivers 168, 170, and the
10 voltage outputs 44c of sensors 172, 174. From these
signals, transmitter 154 derives three RMVs: the
temperature of the process fluid 36a, the density of the
process fluid 36b, and the mass flow rate 36c (derived
from the phase angle between the sensor signals). In
15 addition, transmitter 154 performs uncertainty analyses
to produces three RUs (62a, 62b, 62c), each indicating
the uncertainty of a corresponding RMV 36.

        After generating RMVs 36a-c and RUs 62a-c,
transmitter 154 determines the diagnostic state 58 of
20 flow meter 150. This determination is based on raw data
44a-c, RMVs 36a-c, RUs 62a-c, and auxiliary data 46.
Based on diagnostic state 58, transmitter 154 adjusts the
parameters used in calculating RMVs 36a-c and RUs 62a-c
and recalculates these values. Transmitter 154 then
25 outputs the recalculated RMVs 36a-c and RUs 62a-c as VMVs
26a-c and VUs 28a-c. Transmitter 154 also outputs a MV
status 30a corresponding to temperature, a MV status 30b
corresponding to density, and a MV status 30c
corresponding to mass flow rate. Finally, transmitter
30 154 outputs a single device status 32 corresponding to
the status of flow meter 150.

        Referring again to Fig. 6, the procedure performed
by transmitter 154 during each sample period can be
implemented in software. An example of software for
35 implementing of a self-validating Coriolis meter 150 is

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included in microfiche appendix 1.   In addition, an
example of software for implementing a self-validating
temperature sensor 100 as described above is included in
microfiche appendix 2.   The software in appendices 1 and
5 2 may be implemented on any processor that supports a
structured programming language.   In an alternative
approach, the procedure could be implemented using hard-
wired circuitry.

        The pseudocode shown in Fig. 12 provides a
10 simplified view of the procedure performed by transmitter
154 during each sample period.   Fig. 12 also shows, in
parentheses, the steps performed in Fig. 6 that
correspond to the steps in Fig. 12.   Initially,
transmitter 154 gets raw data 44a-c from flowtube 152
15 (step 200).   Transmitter 154 then calculates RMVs 36a-c
and RUs 62a-c (steps 202-206).   The pseudocode for
calculating RMV 36a and RU 62a is shown in Fig. 13 and is
discussed below.   Next, transmitter 154 examines all
available information (step 208) and determines
20 diagnostic state 58, MV statuses 30a-c, and device status
32 (step 210).   A portion of the pseudocode for
determining diagnostic state 58 and MV statuses 30a-c is
shown in Fig. 14 and discussed below.   Based on
diagnostic state 58, transmitter 154 corrects the
25 parameters used in calculating RMV 36a-c and RU 62a-c
(step 212).   Transmitter 154 then calculates VMVs 26a-c
and VUs 28a-c (steps 214-218) using the procedure with
which RMVs 36a-c and RUs 62a-c were calculated and
corrected parameters.
30   Referring to Fig. 13, transmitter 154 calculates
RMV 36a and RU 62a as follows.   First, transmitter 154
calculates the resistance "R" of temperature sensor 176
(step 250).   Transmitter 154 then calculates the
uncertainty "d_R" of R based on an uncertainty analysis
35 of the equation used to calculate R (step 252).   Next,

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transmitter 154 calculates "temperature" (step 254), and
sets RMV 36a equal to temperature. Finally, transmitter
154 calculates the uncertainty "d_temperature" of
temperature (step 256), and sets RU 62a equal to
5   d_temperature. Thus, as a first pass RMV 36a and RU 62a
equal the measured temperature and its corresponding
uncertainty. If transmitter 154 subsequently determines
that it has less than nominal confidence in RMV 36a and
RU 62a, transmitter 154 modifies any of the parameters,
10 uncertainties, and/or raw data (e.g., RK1, d_RK1, f_RTD)
used in calculating temperature and d_temperature to
reflect the impact of an expected fault. Transmitter 154
then reperforms the procedure illustrated in Fig. 13
using the modified information and sets VMV 26a and VU
15 28a equal to the new values for temperature and
d_temperature. Alternatively, if transmitter 154
determines that the fault is too severe, transmitter 154
may set VMV 26a and VU 28a based on historical data.

        Fig. 14 illustrates the procedure used by
20 transmitter 154 to detect and respond to a loss of input
from temperature sensor 176. Transmitter 154 maintains a
variable, RTD_input_state, that indicates the current
status of the input from temperature sensor 176. As a
first step, transmitter 154 checks RTD_input state (step
25 300).

        If RTD_input_state equals RTD_INPUT_OK, which
indicates that the input from temperature sensor 176 was
functioning normally during the previous sample period,
transmitter 154 checks the resistance of temperature
30 sensor 176 (step 304). If the resistance is less than 80
ohms, this indicates that the connection between
transmitter 154 and temperature sensor 176 has been lost.
In response, transmitter 154 sets RTD_input_state to
RTD_INPUT_LOST (step 306). Transmitter 154 then checks
35 the value of RTD_spike_state, which indicates whether

transmitter 154 had sensed a spike in the output from
temperature sensor 176 during the previous sample (step
308). If RTD_spike_state indicates that a spike had
occurred, transmitter 154 resets RTD_input_state to
5 indicate no spike (step 310). (A spike is a less serious
fault and is mooted by the loss of connection.)

      If RTD_input_state equals RTD_INPUT_LOST,
transmitter 154 checks the resistance of temperature
sensor 176 (step 314). If the resistance is less than
10 100 ohms (step 314), this indicates that connection with
temperature sensor 176 is still lost. (Different
resistance values are used in steps 304 and 314 to avoid
intermittent switching of RTD_input_state if, for
example, the resistance fluctuates between 79 and 81
15 ohms.) If connection is lost, transmitter 154 sets MV
status 30a, which corresponds to temperature, to BLIND
(step 316) and substitutes historical information (step
318) about temperature for use in the recalculation steps
(steps 214-18 of Fig. 12). Because density and mass flow
20 are based, in part, on temperature, transmitter 154 sets
MV statuses 30b-c to BLURRED (steps 320-22). If the
resistance is greater than 100 ohms, transmitter 154 sets
RTD_input state to RTD_INPUT_RECOVER, to indicate that
connection has been reestablished (step 326). At this
25 time, transmitter 154 initializes a recovery timer by
setting RTD_input_count equal to zero (step 328).

      If RTD_input_state equals RTD_INPUT_RECOVER,
transmitter 154 merges the past and present values for
temperature as discussed above (step 332). Transmitter
30 154 then checks to see if the recovery timeout period has
expired (step 334). If it has, transmitter 154 sets
RTD_input_state to RTD_INPUT_OK (step 336). If it has
not, transmitter 154 sets MV status 30a to BLURRED (step
340) and increments RTD_input_count (step 342).

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Fig. 15 illustrates the response of flow meter 150 to a loss of input from temperature sensor 176. At time 9, the loss of input occurs and the unvalidated temperature measurement, RMV 36a, begins to rapidly drop.

5 At time 10, transmitter 154 sets diagnostic state 58 to indicate that a spike in the temperature input has occurred, and, in response, changes MV status 30a to DAZZLED, modifies VMV 26a and VU 28a based on past performance as discussed above, and leaves MV statuses

10 30b-c, VMVs 26b-c, and VUs 28b-c unchanged (though, because density and mass flow rate are partially dependent on temperature, VMVs 26b-c and VUs 28b-c include the changes to VMV 26a and VU 28a).

At time 12, the resistance of temperature sensor

15 176 drops sufficiently low that transmitter 154 sets diagnostic state 58 to indicate that a loss of temperature input has occurred, and, in response, changes MV status 30a to BLIND, continues to base VMV 26a and VU 28a on past performance, changes MV statuses 30b-c to

20 BLURRED, and leaves VMVs 26b-c unchanged. Because the uncertainties of density and mass flow are based in part on the uncertainty of temperature, VUs 28b-c will increase to reflect the increase in VU 28a.

At time 48, the resistance of temperature sensor

25 176 increases to a sufficient level so that transmitter 154 sets diagnostic state 58 to indicates that temperature input has been recovered, and, in response, changes MV status 30a to BLURRED, initializes a recovery timer, begins merging past and present values for VMV 26a

30 and VU 28a, and changes MV statuses 30b-c to CLEAR.

At time 72, the recovery timer expires, and transmitter 154 sets diagnostic state 58 to indicate that the temperature input is fully recovered, and, in response, changes MV status 30a to CLEAR and bases VMV

35 26a and VU 28a on RMV 36a and RU 62a.

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Other embodiments are within the following claims.

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5 facsimile reproduction by anyone of the patent document or patent disclosure, as it appears in the Patent and Trademark Office file or records, but otherwise reserves all copyright rights whatsoever.

What is claimed is:

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Claims

1.   A sensor for providing a measurement and
information about the validity of the measurement, said
sensor comprising:
5   a transducer for generating a data signal related
to the value of a variable and
           a transmitter for receiving said data signal and
generating in response thereto a first output signal
indicating a measurement of said variable and a second
10 output signal based on a dynamic uncertainty analysis of
said first output signal.

2.   The sensor of claim 1, wherein, when said
sensor experiences a fault, said transmitter modifies
said first and second output signals to account for an
15 impact of said fault.

3.   The sensor of claim 1, wherein said
transmitter generates a third output signal that
indicates a state of reliability of said first output
signal.

20   4.   The sensor of claim 1, said sensor further
comprising a plurality of transducers that generate a
plurality of data signals related to the value of one or
more variables, wherein said transmitter generates said
first output signal based on one or more of said data
25 signals.

5.   A sensor for providing measurements and
information about the validity of the measurements, said
sensor comprising:
           one or more transducers for generating a first
30 data signal related to the value of a first variable and

a second data signal related to the value of a second variable,

a transmitter for receiving said first and second data signals and generating in response thereto a first
5   output signal related to a measurement of said first variable, a second output signal based on a dynamic uncertainty analysis of said first output signal, a third output signal related to a measurement of said second variable, and a fourth output signal based on a dynamic
10 uncertainty analysis of said third output signal.

6.   The sensor of claim 5, wherein, when said sensor experiences a fault, said transmitter modifies said first, second, third, and fourth output signals to account for an impact of said fault.

15   7.   The sensor of claim 5, wherein said transmitter generates a fifth output signal that indicates a state of reliability of said first output signal.

8.   The sensor of claim 7, wherein said
20 transmitter generates a sixth output signal that indicates a state of reliability of said third output signal.

9.   The sensor of claim 8, wherein said transmitter generates a seventh output signal that
25 indicates an operational status of said sensor.

10.   The sensor of claim 5, wherein said sensor includes a plurality of transducers.

11.   The sensor of claim 5, wherein said sensor includes a single transducer.

12.   A method of providing a measurement and information about the validity of the measurement comprising the steps of:

　　　　receiving a data signal related to the value of a
5　variable;

　　　　based on said data signal, estimating a measurement of said variable;

　　　　generating a first output signal related to the estimated measurement of said variable;

10　　　　performing an uncertainty analysis of said first output signal; and

　　　　generating a second output signal based on said uncertainty analysis.

13.   The method of claim 12, said method further
15　including the step of determining whether said data signal is faulty, wherein, when said data signal is faulty, said estimating step modifies said estimated measurement to account for an impact of said fault.

14.   The method of claim 13, wherein, when said
20　data signal is faulty, said uncertainty analysis accounts for an impact of said fault.

15.   The method of claim 12, said method further including the step of generating a third output signal that indicates a state of reliability of said first
25　output signal.

16.   The method of claim 12, said method further including the step of receiving a plurality of data signals, wherein said estimating step estimates the measurement of said variable based on said plurality of
30　data signals.

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17. A method of providing measurements and information about the validity of the measurements comprising the steps of:

    receiving a first data signal related to the value
5 of a first variable;

    receiving a second data signal related to the value of a second variable;

    based on said first data signal, estimating a measurement of said first variable;

10   generating a first output signal related to the estimated measurement of said first variable;

    performing an uncertainty analysis of said first output signal;

    generating a second output signal based on said
15 uncertainty analysis of said first output signal;

    based on said second data signal, estimating a measurement of said second variable;

    generating a third output signal related to the estimated measurement of said second variable;

20   performing an uncertainty analysis of said third output signal; and

    generating a fourth output signal based on said uncertainty analysis of said third output signal.

18. The method of claim 17, said method further
25 including the step of determining whether said first data signal is faulty, wherein, when said first data signal is faulty, said estimating step modifies said estimated measurement of said first variable to account for an impact of said fault.

30   19. The method of claim 18, wherein, when said first data signal is faulty, said uncertainty analysis of said first output signal accounts for an impact of said fault.

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20.   The method of claim 17, said method further including the step of determining whether said second data signal is faulty, wherein, when said second data signal is faulty, said estimating step modifies said

5   estimated measurement of said second variable to account for an impact of said fault.

21.   The method of claim 20, wherein, when said second data signal is faulty, said uncertainty analysis of said third output signal accounts for an impact of

10   said fault.

22.   The method of claim 17, said method further including the step of generating a fifth output signal that indicates a state of reliability of said first output signal.

15   23.   The method of claim 22, said method further including the step of generating a sixth output signal that indicates a state of reliability of said third output signal.

24.   A temperature sensor for providing a
20   temperature measurement and information about the validity of the temperature measurement, said temperature sensor comprising:
      a transducer for generating a data signal related to a temperature and
25   a transmitter for receiving said data signal and generating in response thereto said temperature measurement and an uncertainty signal based on a dynamic uncertainty analysis of said temperature measurement.

25.   The sensor of claim 24 wherein, when said
30   temperature sensor experiences a fault, said transmitter

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modifies said temperature measurement and said
uncertainty signal to account for an impact of said
fault.

       26.   The sensor of claim 24, wherein said
5 transmitter generates a third output signal that
indicates a state of reliability of said temperature
measurement.

       27.   A Coriolis flow meter for providing
measurements of mass flow, density, and temperature and
10 information about the validity of the measurements, said
Coriolis flow meter comprising:
       one or more transducers for generating a first
data signal related to mass flow, a second data signal
related to density, and a third data signal related to
15 temperature,
       a transmitter for receiving said first, second,
and third data signals and generating in response thereto
a mass flow measurement signal, a first uncertainty
signal based on a dynamic uncertainty analysis of said
20 mass flow measurement signal, a density measurement
signal, a second uncertainty signal based on a dynamic
uncertainty analysis of said density measurement signal,
a temperature measurement signal, and a third uncertainty
signal based on a dynamic uncertainty analysis of said
25 temperature measurement signal.

       28.   The Coriolis flow meter of claim 27, wherein,
when said Coriolis flow meter experiences a fault, said
transmitter modifies said measurement signals and said
uncertainty signals to account for an impact of said
30 fault.

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29.   The Coriolis flow meter of claim 27, wherein
said transmitter generates a first reliability signal
that indicates a state of reliability of said mass flow
measurement signal, a second reliability signal that
5 indicates a state of reliability of said density
measurement signal, and a third reliability signal that
indicates a state of reliability of said temperature
measurement signal.

30.   The Coriolis flow meter of claim 29, wherein
10 said transmitter generates a operational status signal
that indicates an operational status of said Coriolis
flow meter.
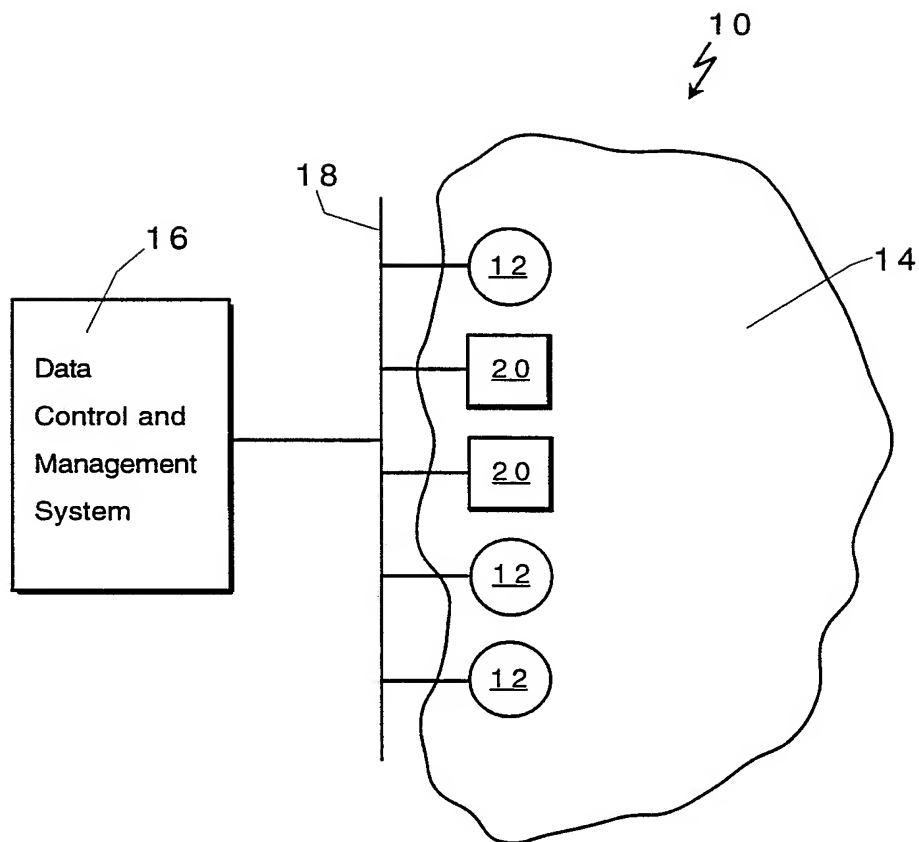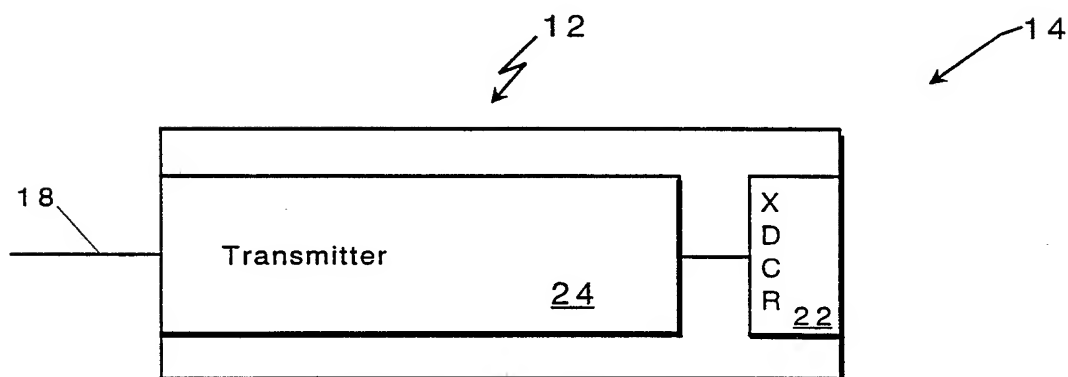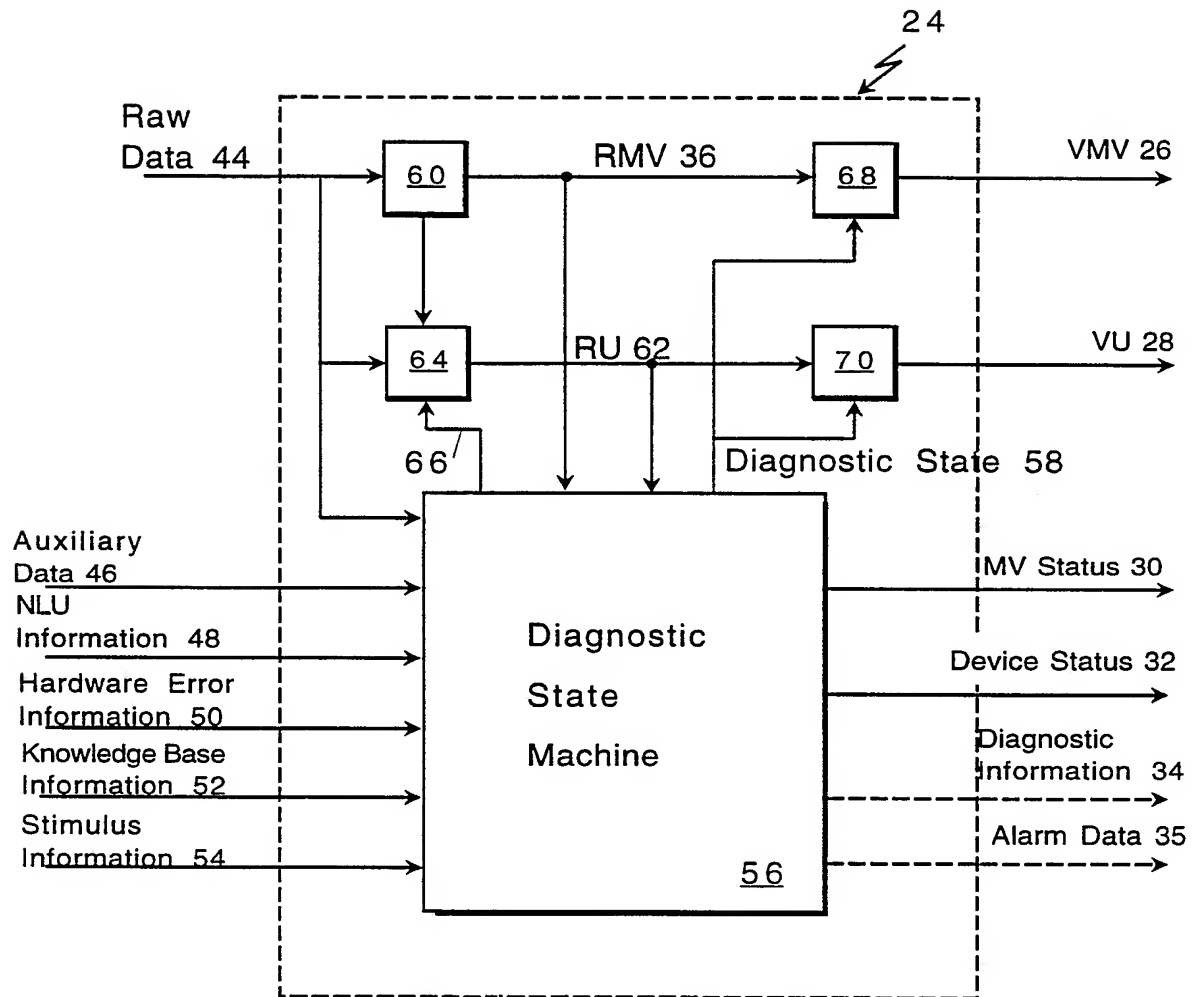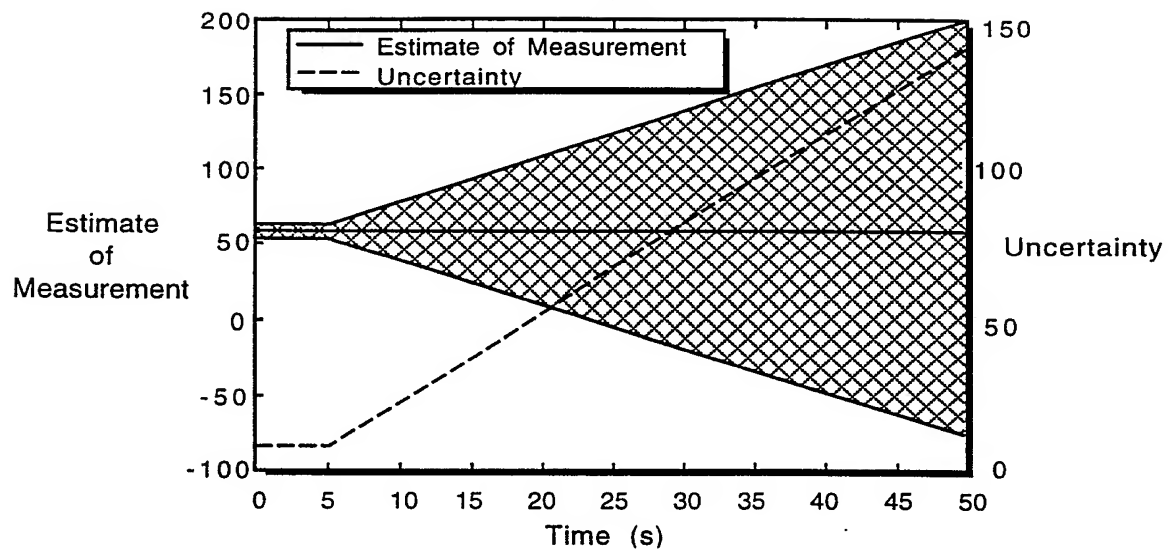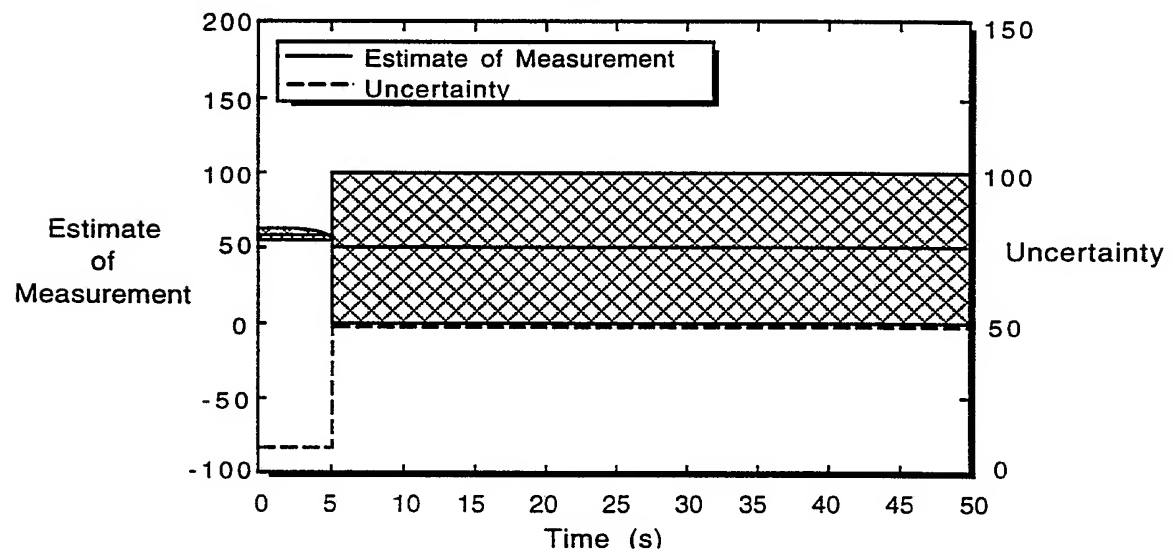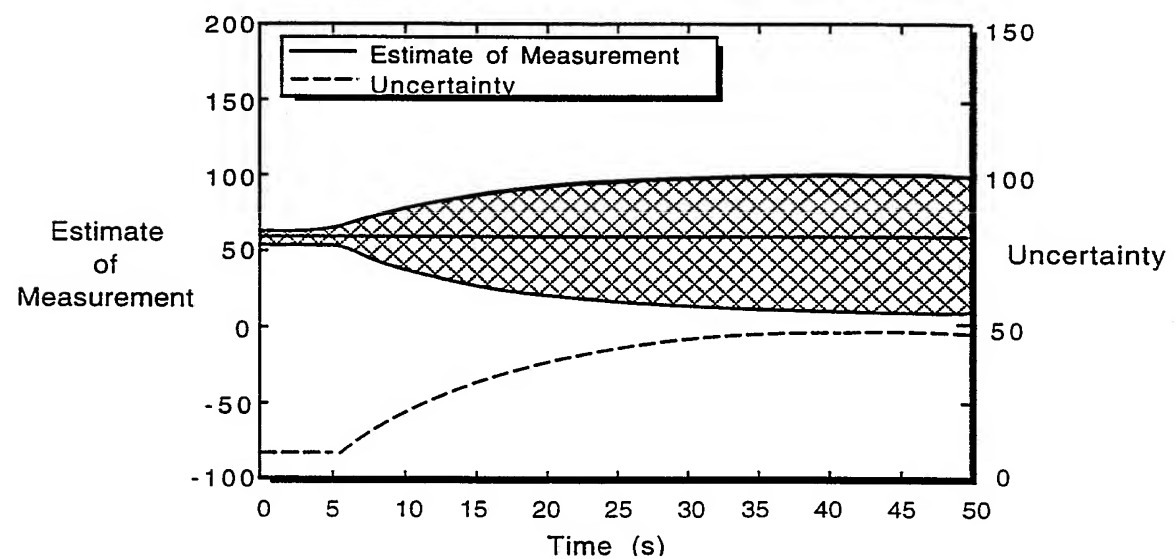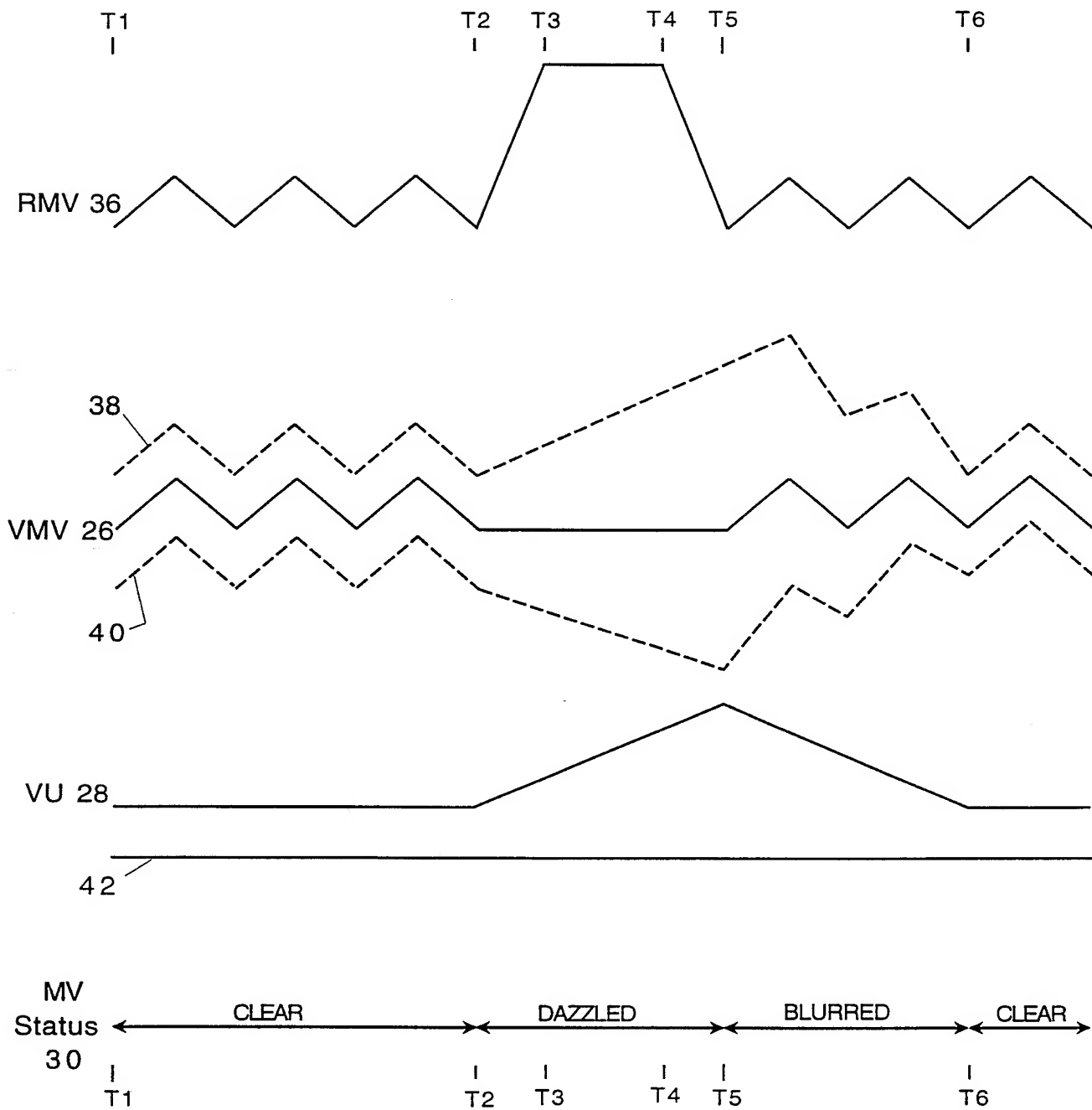
10

18

16

14

Data
Control and
Management
System

12

20

20

12

12

FIG. 1

12

14

18

Transmitter

24

X
D
C
R

22

FIG. 2

2/16

FIG. 3

FIG. 4a

FIG. 4b

FIG. 4c

RMV 36

38

VMV 26

40

VU 28

42

MV
Status
30

CLEAR   DAZZLED   BLURRED   CLEAR

T1   T2   T3   T4 T5   T6

FIG. 5
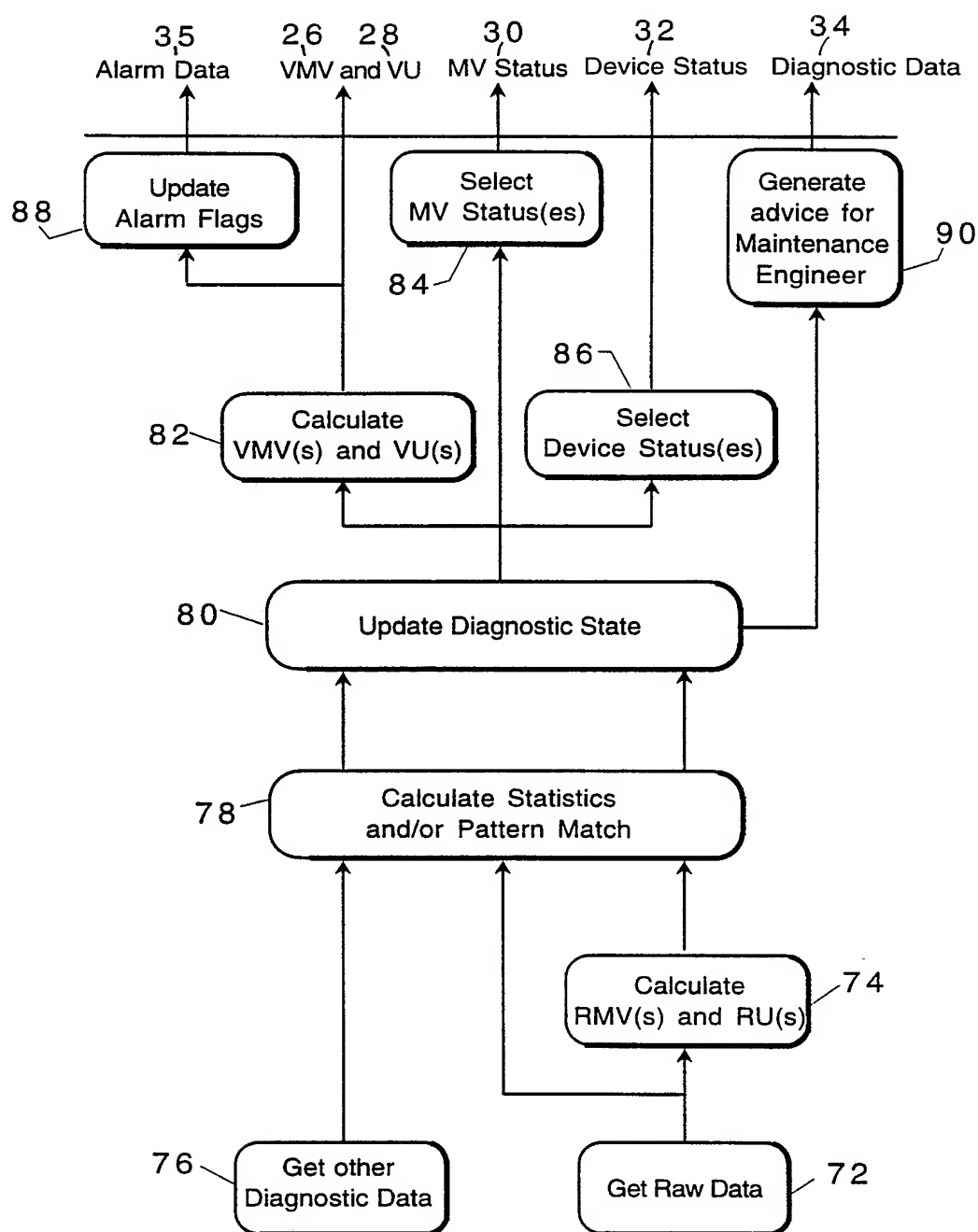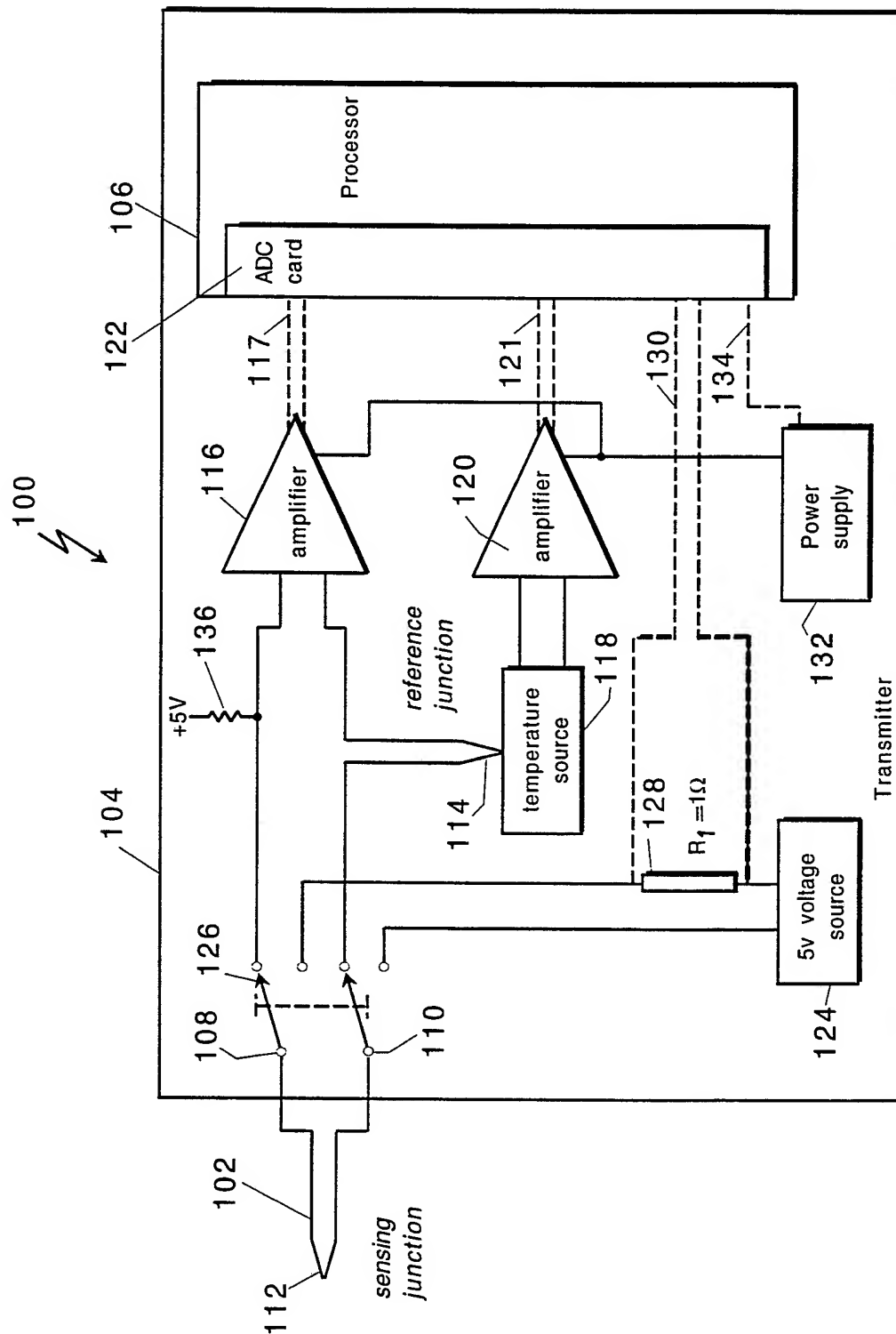
FIG. 6

FIG. 7
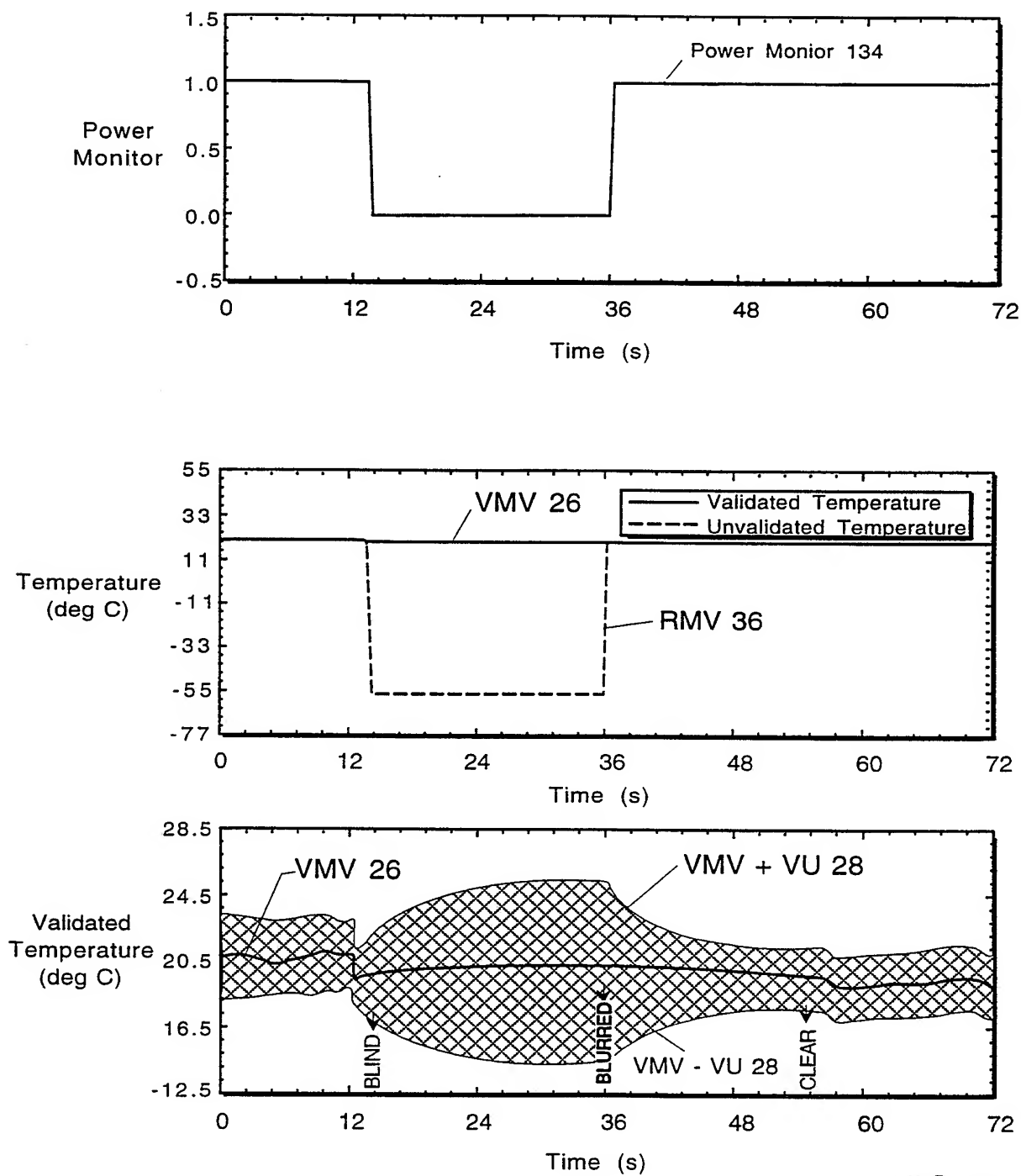
FIG. 8
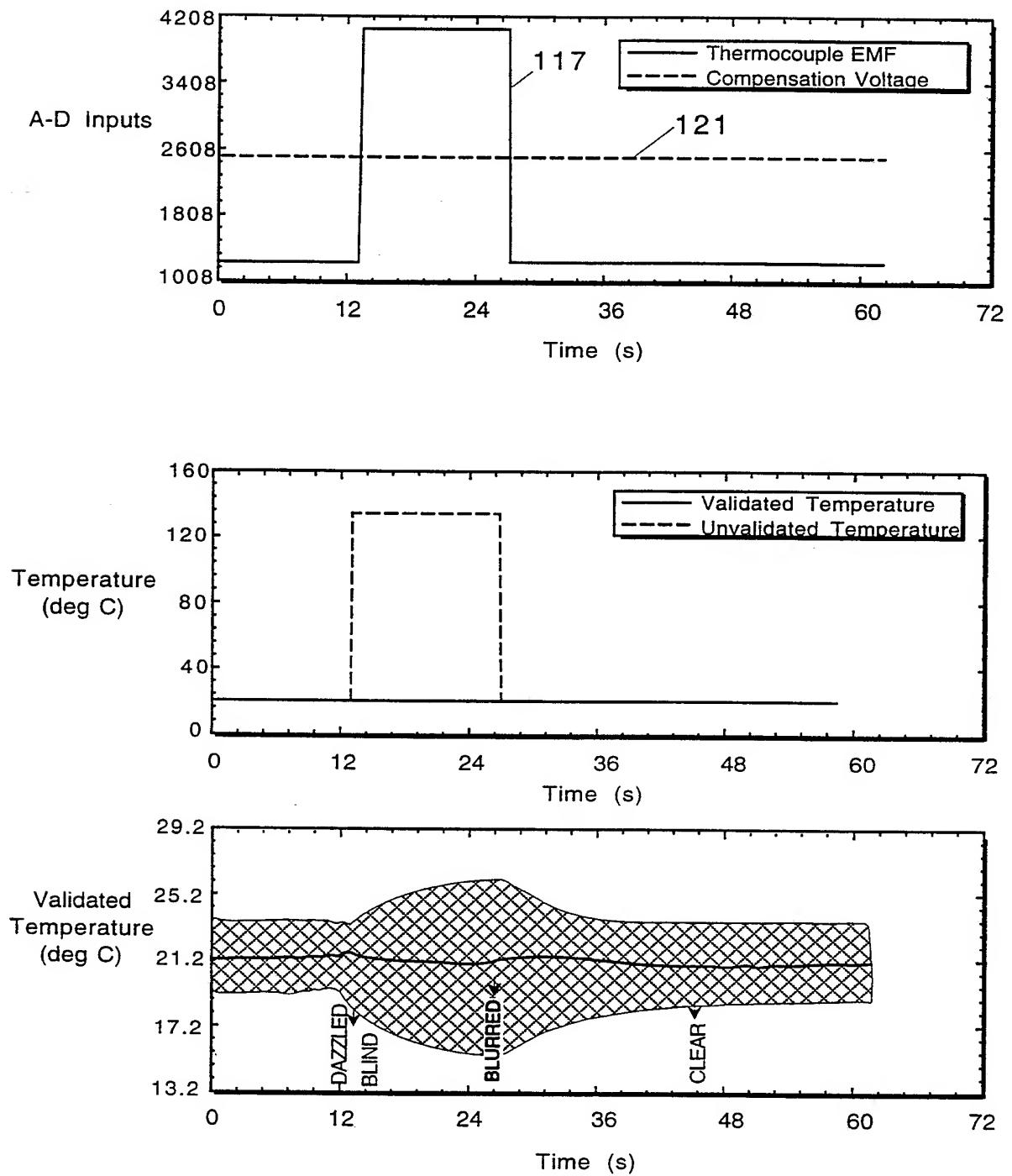
FIG. 9
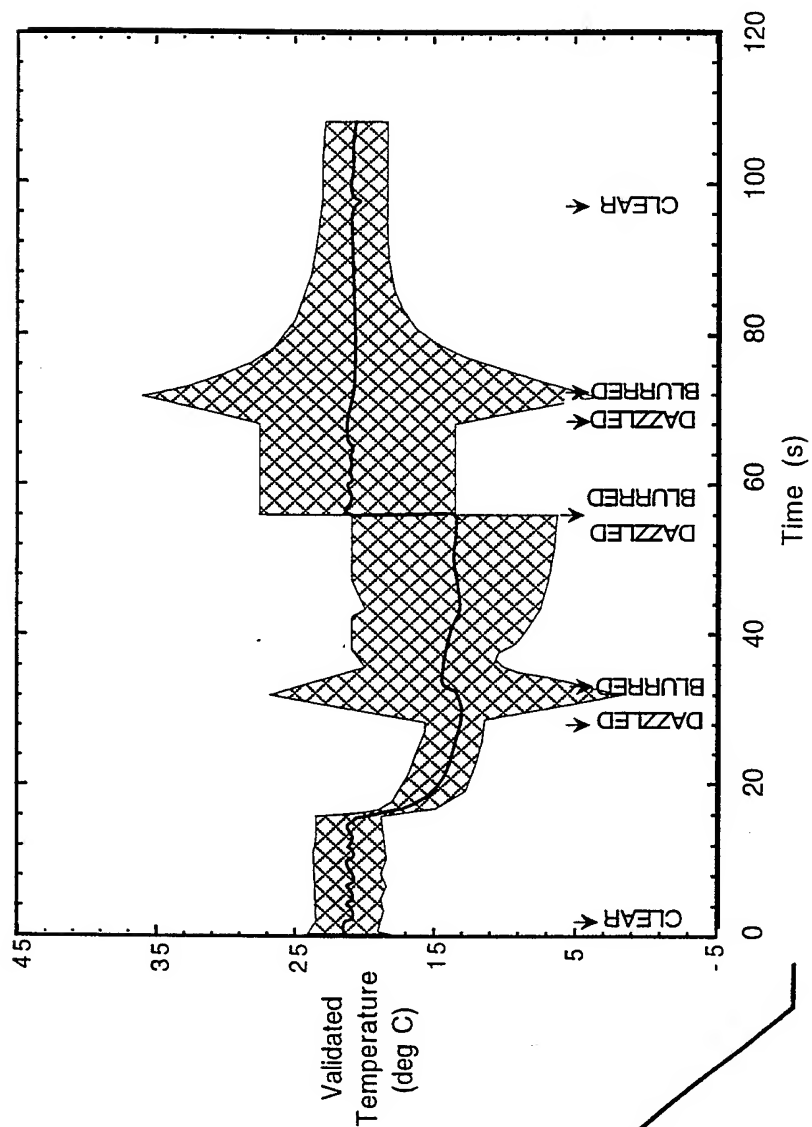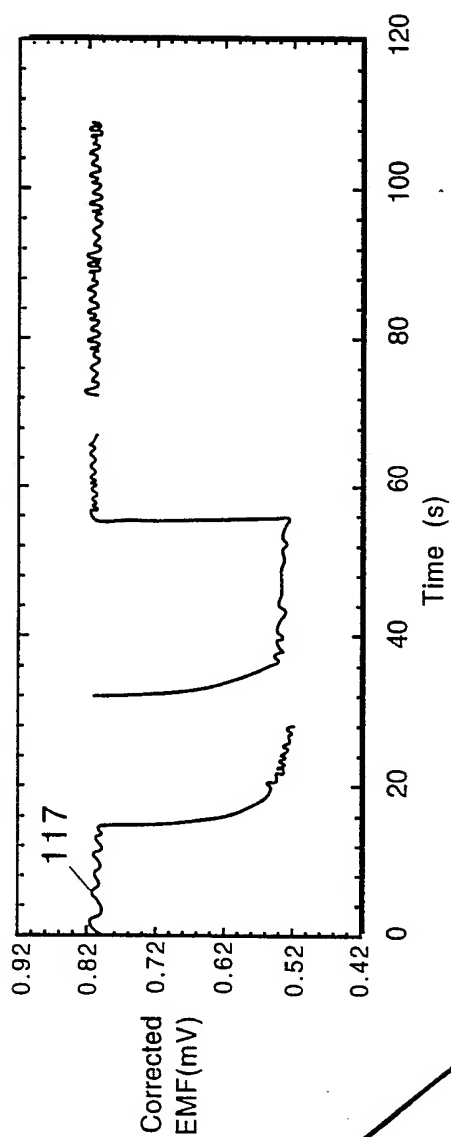
FIG. 10
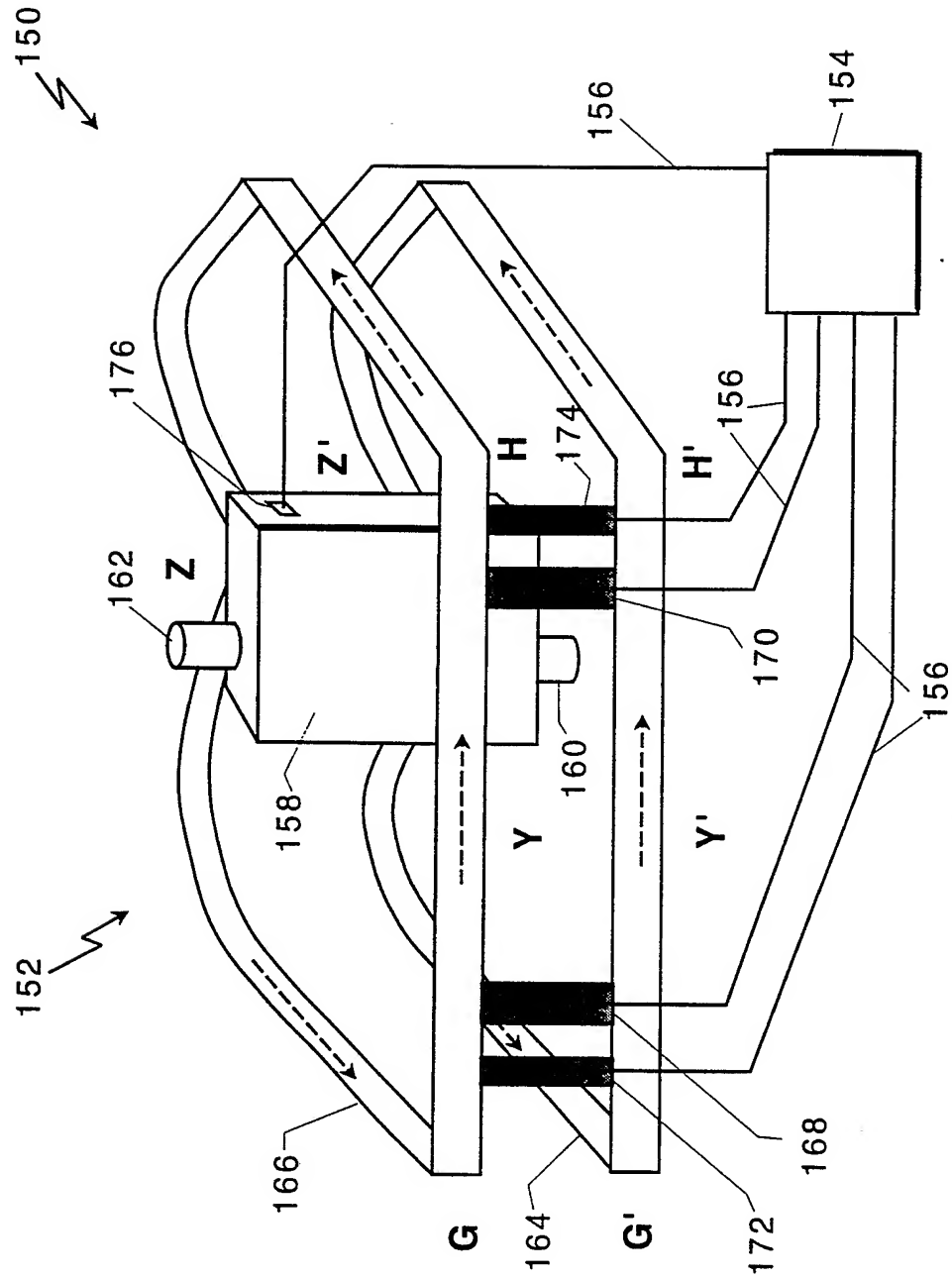
FIG. 11

Step/ (Fig. 6 step)	Action
200 (72)	Get raw data.
202 (74)	Calculate temperature RMV and RU.
204 (74)	Calculate density RMV and RU.
206 (74)	Calculate mass flow RMV and RU.
208 (74)	Consider all inputs.
210 (78, 80, 84, 86)	Make diagnosis.
212 (80)	Correct all inputs.
214 (82)	Calculate temperature VMV and VU.
216 (82)	Calculate density VMV and VU.
218 (82)	Calculate mass flow VMV and VU.

FIG. 12

Step	Action
250	R = (RK1 * tran_temp + RK2) * f_RTD + RK3 * tran_temp + RK4

> [RK1-4 are calibration constants, tran_temp is the temperature of transmitter 154, and f_RTD is the frequency of the signal coming out of RTD temperature sensor 176.]

252	d_R = sqrt (

$$
\begin{aligned}
& \text{sqr (tran\_temp * f\_RTD * d\_RK1) +} \\
& \text{sqr (f\_RTD * d\_RK2) +} \\
& \quad \text{sqr (tran\_temp * d\_RK3) +} \\
& \quad \text{sqr (d\_RK4) +} \\
& \quad \text{sqr ((RK1 * f\_RTD + RK3) *} \\
& \qquad \text{d\_tran\_temp) +} \\
& \quad \text{sqr ((RK1 * tran\_temp + RK2) *} \\
& \qquad \text{d\_f\_RTD))}
\end{aligned}
$$

> [d_x is the uncertainty of x.]

254	temperature = RTD_A * R * R + RTD_B * R + RTD_C
256	d_temperature = (2.0 * RTD_A * R + RTD_B) * d_R

FIG. 13

Step	Action
300	Check RTD_ input_state
302	If RTD_INPUT_OK
304	If RTD_ resistance < 80.0
306	RTD_input_state = RTD_INPUT_LOST
308	If RTD_spike_state <> RTD_SPIKE_OFF
310	RTD_spike_state = RTD_SPIKE_OFF
312	If RTD_INPUT_LOST
314	If RTD_ resistance < 100.0
316	Temperature MV status = BLIND
318	Substitute historical temperature
320	Density MV status = BLURRED
322	Mass Flow MV status = BLURRED
324	Else
326	RTD_input_state = RTD_INPUT_RECOVER
328	RTD_input_count = 0
330	If RTD_INPUT_RECOVER
332	Merge past and present temperature
334	If RTD_input_count = 90
336	RTD_input_state = RTD_INPUT_OK
338	Else
340	Temperature MV status = BLURRED
342	Increment RTD_input_count

FIG. 14
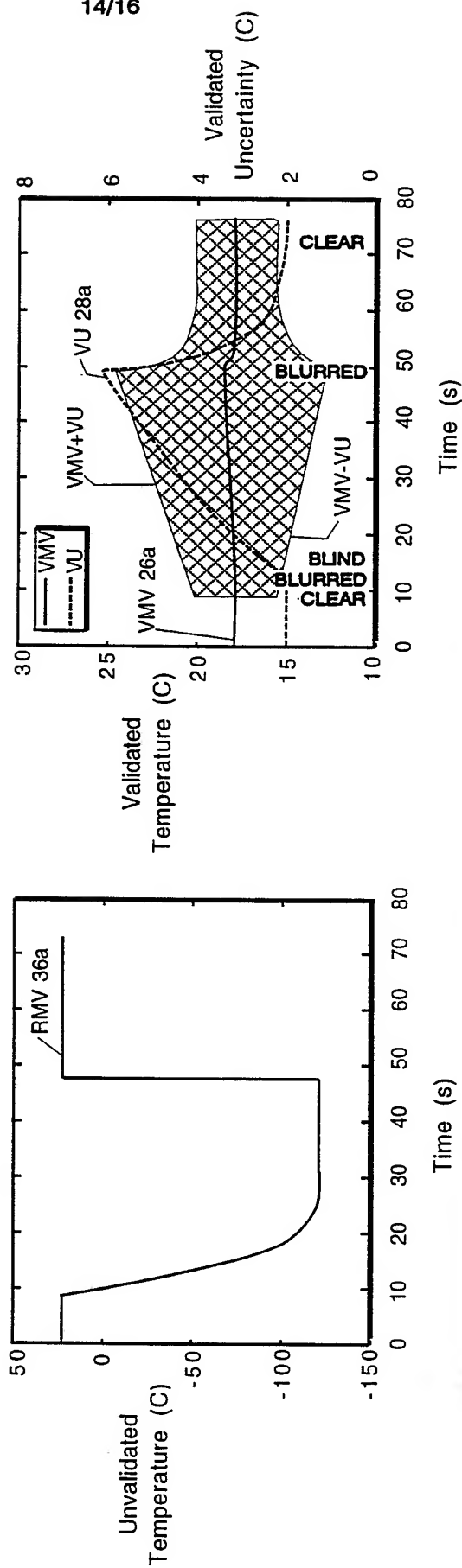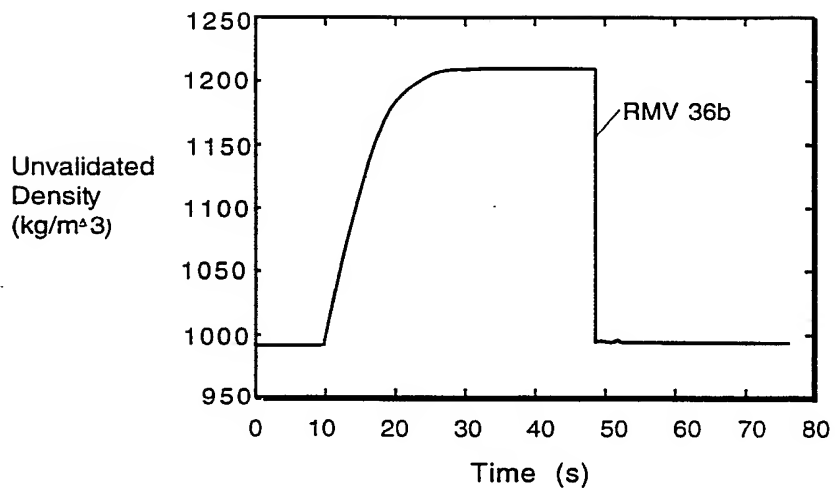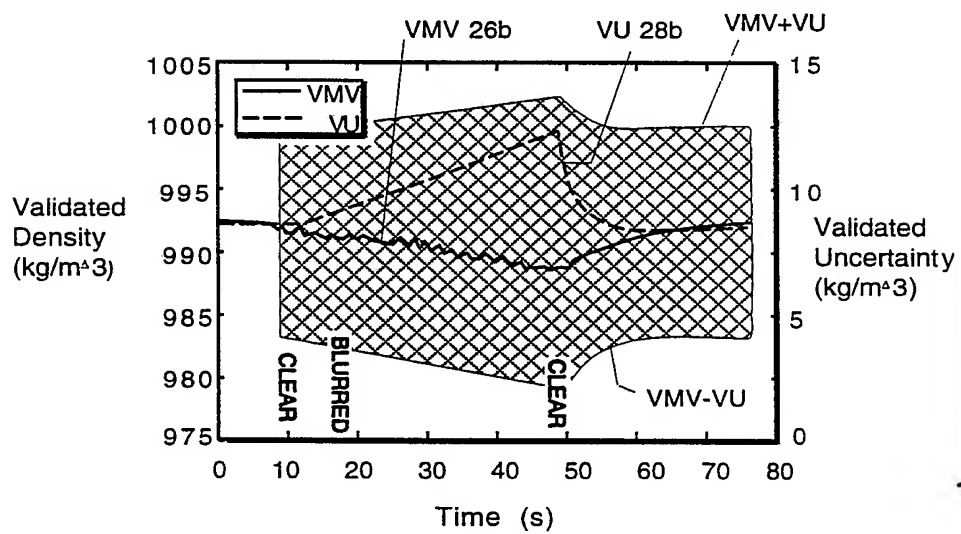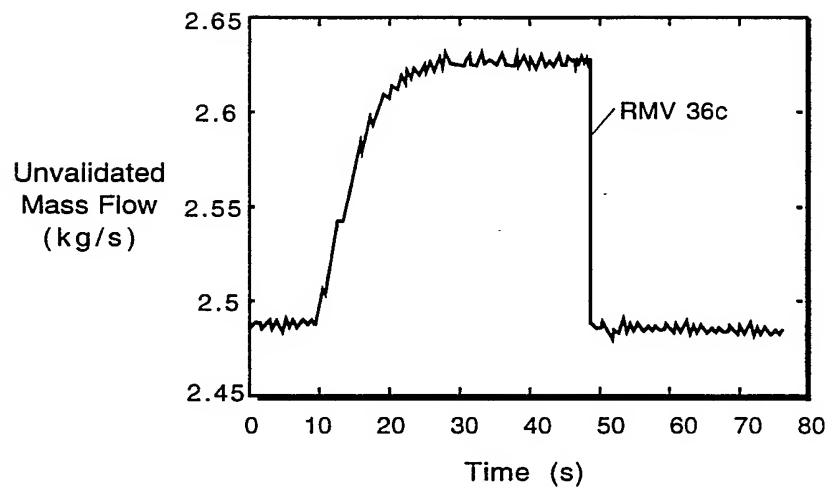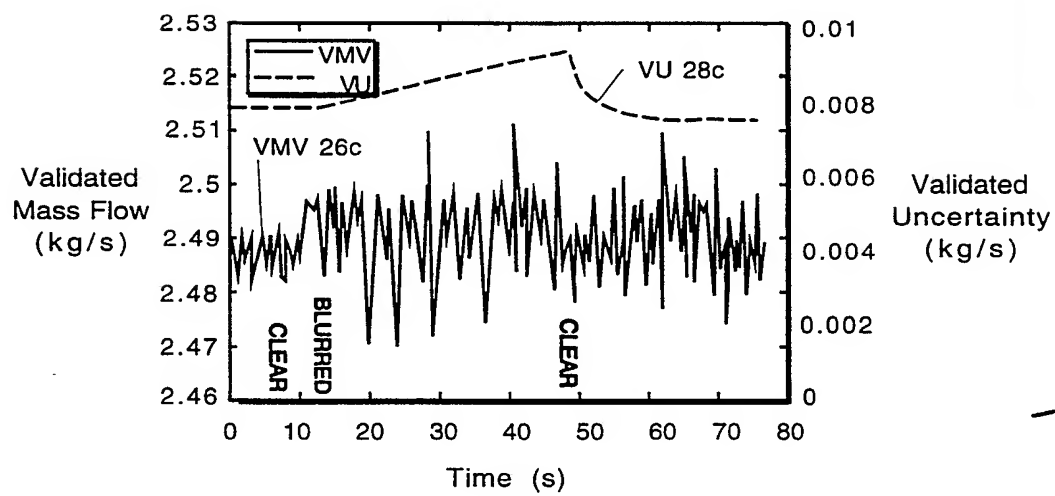
FIG. 15a

FIG. 15b

FIG. 15c

I. CLASSIFICATION OF SUBJECT MATTER   (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 G01K15/00;   G01F1/84

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	G01K ; G01F

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category[o]	Citation of Document,[11] with indication, where appropriate, of the relevant passages[12]	Relevant to Claim No.[13]
X	FR,A,2 334 827 (GENERAL ELECTRIC CO) 8 July 1977 see page 3, line 30 – page 5, line 12 see page 7, line 7 – page 11 ---	1-5, 12-17,24
X	COLLOQUIM DIGEST-IEE 11 February 1991, BOSTON pages 1 – 2 M.P. HENRY 'A FAULT-TOLERANT INTERFACE FOR SELF-VALIDATING SENSORS' see the whole document ---	1
X	EP,A,0 413 814 (TERUMO) 27 February 1991 see page 2, line 36 – line 55; figures ---	1,2,12, 13,24
X	US,A,4 934 196 (PAUL ROMANO) 19 June 1990 see abstract; figures ---	1-3, 27-30

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[o] Special categories of cited documents : [10]

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
07 JULY 1993	21. 07. 93

International Searching Authority	Signature of Authorized Officer
EUROPEAN PATENT OFFICE	RAMBOER P.

III. DOCUMENTS CONSIDERED TO BE RELEVANT	(CONTINUED FROM THE SECOND SHEET)	
Category°	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
X	EP,A,0 122 622 (OMRON TATEISI) 24 October 1984 see abstract ---	1,3,24
A	DE,C,3 540 204 (DAIMLER-BENZ) 25 September 1986 see the whole document -----	24,25

ANNEX TO THE INTERNATIONAL SEARCH REPORT
ON INTERNATIONAL PATENT APPLICATION NO.

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The members are as contained in the European Patent Office EDP file on
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